

A SYSTEM TO ANALYZE CONTINUOUS INK JET DROPLETS

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Ink jet technologies – also known as microdrop technologies – are receiving increased interest in applications outside of traditional printing and marking. Because of this, methods and procedures are necessary to evaluate components and fluids of designs for non-printing applications. Much attention has been spent on drop on demand (DOD) printing due to its large commercial availability, which has caused continuous ink jet (CIJ) printing to be neglected. This issue is addressed by developing procedures to photograph droplets produced by a CIJ printer in the absence of charging and deflection. Both an OEM printer and a custom experimental setup are used to supply fluid pressure and modulation voltage to a CIJ modulator and nozzle. The resultant droplets are photographed with two different camera systems, and analyzed with Matlab and ImageJ. With these programs, methods are presented to analyze the velocity, volume, drop production rate, and spacing of the droplets so that these factors can be evaluated in the design of a new system that uses CIJ technology.

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PREFACE

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1.0 INTRODUCTION

1.1 BACKGROUND

The use of inkjet technologies – also commonly known as microdrop technologies – has witnessed an increased level of research and applications outside of traditional printing[1]. Personal and industrial devices that have been developed for several decades have fine-tuned the technology in terms of precision and cost. Resources for the technology are widely accessible due to the commercial availability of the technology, and the low impact nature of the technology is extremely attractive for a wide variety of applications.

For these same reasons recent research into new applications has focused on a style of inkjet technology referred to as drop on demand (DOD), the standard printing style found in personal printers. Continuous ink jet (CIJ) printing is a printing technology that is not as widely commercially available as DOD printing, and has been neglected because of such reduced accessibility. Nonetheless, CIJ printing has many distinct advantages over DOD printing, and is worthy of investigation. Specifically, this thesis investigates the technologies of fluid modulation and ejection in the CIJ.

1.2 PROBLEM STATEMENT

The purpose of this thesis is to develop a system consisting of hardware, software and procedures that will allow a CIJ designer to analyze the ink drops created by the CIJ technology. This system will allow the designer to manipulate controllable factors such as system pressure, modulation voltage, and modulation frequency. Characteristics such as ink drop volume, spacing, drop production rate, and velocity, which are factors in the quality of the CIJ system, are

to be observed and evaluated by the system. Such a system with these capabilities will be highly desirable to CIJ design because it will eliminate trial and error methods of testing and evaluation and allow precise measurement of system characteristics.

1.3 APPROACH TO THE PROBLEM

Both an OEM CIJ printer and a custom printing apparatus that could control the modulation voltage, modulation frequency, and fluid pressure were used in the analysis. For the custom test unit, the OEM CIJ printer was used to reproduce the modulation circuitry and a fluid pump of similar specifications to what is used on the OEM printer to supply water to a fluid ejection system of similar design to an OEM print head associated with the OEM printer. This system allowed the system pressure, modulation voltage, and modulation frequency to be adjusted. In each experimental setup, the same fluid ejection system was used.

Resultant fluid drops were captured with two types of imaging systems. The first consisted of a Nikon digital camera coupled to a microscope. This system was used solely for imaging ink drops produced by the OEM printer. The second consisted of a Sensicam high-speed camera with a microscopic lens, used in conjunction with the custom system.

To analyze the captured drops for volume, spacing, and velocity the photographs were processed with the image analysis software ImageJ, and the mathematical software package Matlab, and associated numerical methods were developed to measure the desired variables. Results from each method were compared to evaluate their accuracy and consistency.

2.0 CONTINUOUS INK JET OPERATION

2.1 BASIC PRINCIPLES

CIJ printing is a method of marking where an ink stream is continuously run under pressure, and a sinusoidal agitation of the fluid allows the fluid to break up into a train of droplets. Although fluid streams will naturally break up to some extent at a given distance, this sinusoidal agitation forces the stream to break up closer to the nozzle exit, controllably, and consistently. A piezo crystal in contact with the fluid is typically used to provide this sinusoidal agitation. As the stream breaks into droplets, these droplets pass through what is called a charge tunnel made of conductive material and connected to a quantizer. Each droplet is given an individual charge as it passes through the charge tunnel. Once through the charge tunnel the droplets enter a constant electrostatic field and deflect from their flight path at an angle proportional to how much charge was induced upon them in the charge tunnel. This electrostatic field is produced by what are called deflection plates that are connected to a high voltage DC power source. Droplets not to be deflected are given a negligible charge and therefore experience negligible deflection. A return system collects the droplets that are not directed to the substrate so as to reuse the ink. CIJ printing can thus be divided into four essential features that define its operation: modulation, charging, deflection, and collection.

Applications of CIJ printing include product labeling in the food and beverage industry, bar coding, and various other product marking situations. Because of this variety of media possible substrates include - but are not limited to - paper, plastic, glass, metal, and wood. The object to be marked is physically moved perpendicular to the direction of deflection.

An illustration of the concept of CIJ printing and the components essential to its operation is given in Figure 1. In this illustration, droplets of different magnitudes of deflection are given different shades of grey to emphasize this characteristic. The process has no effect on the color of the droplets, which is only dependent on the ink used. An original Linx MIDI CIJ

print head is shown in Figure 2, and an example of it in operation is shown in Figure 3. It can be seen that as the print head is moving horizontally from left to right, the print head deflects the ink vertically to create text.

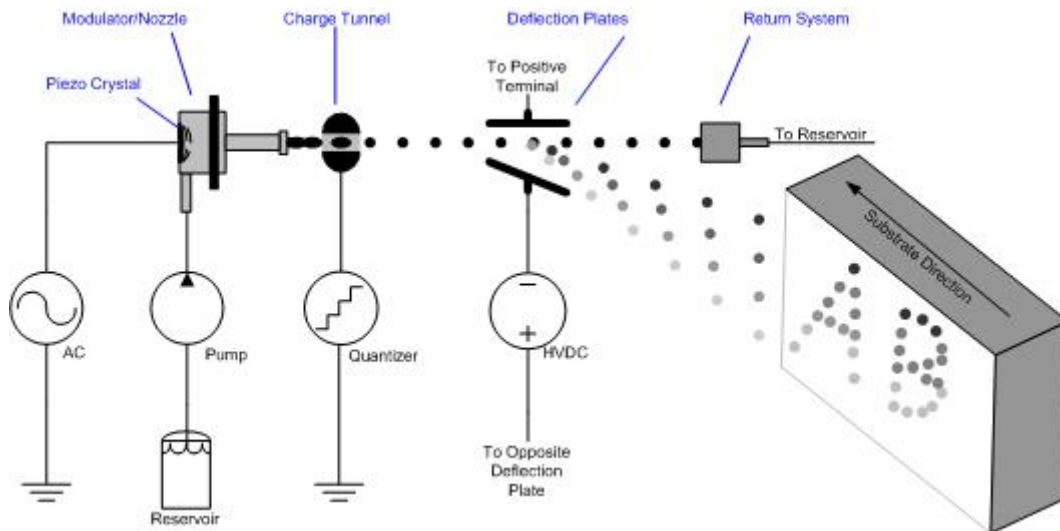


Figure 1: Illustration of Continuous Ink Jet Printing



Figure 2: Original Linx Print Head

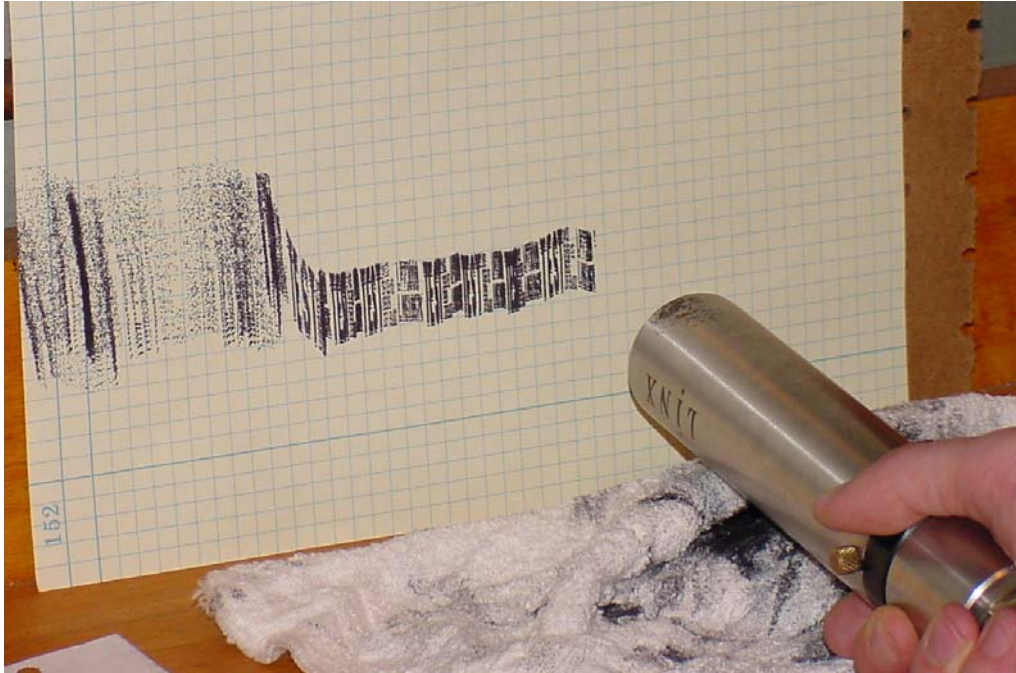


Figure 3: Print Head in Operation

2.2 FLUID EJECTION SYSTEM

The focus of this thesis is the droplets produced by the CIJ system in the absence of charging, deflection, and collection. Components responsible for modulating the fluid stream and releasing the fluid into the atmosphere will henceforth be referred to as the fluid ejection system.

The main components of the fluid ejection system are the modulator and nozzle. While the modulator was of identical design to that found in the Linx MIDI CIJ print head (shown in Figure 2), the nozzle was modified. Although the nozzle's physical characteristics are different than that of the original, its functionality has not been disturbed. A printed circuit board (PCB) based on the Linx MIDI CIJ print head was used to hold the nozzle and modulator in place. Excess material was removed from the PCB so that the minimum amount of material necessary to hold the components remained.

Fluid was supplied to the modulator feed line with 0.0625-inch inner diameter, 0.125-inch outer diameter Teflon tubing. A return line also exists to control the pressure or flush the system. These lines are interchangeable. Modulation of the fluid was actuated by a bimorph piezo crystal (Morgan Matroc, 62155) that was in contact with the fluid. Voltage was supplied to the piezo crystal with a RG174/U 50 Ohm coaxial cable. The inner conductor of the coaxial cable was connected to a 24-gauge wire, which supplied the signal to the piezo crystal with a flat brass ring. The outer conductor connected the modulator body to ground, which effectively connected the fluid in the modulator to ground as well. A Teflon seal allows the piezo crystal to contact the fluid without fluid leaking out of the system. As an extra measure of protection GE TSE397-C silicone rubber was applied to the modulation wire entrance to protect the wire insulation and components inside the modulator body from caustic materials.

The modulator was coupled to the nozzle on the printed circuit board, and proper fluid sealing was accomplished with an o-ring. For the fluid exit, an orifice with a 60-micron diameter (Swiss Jewel, P/N A2.00) was used. Both the modulator and nozzle were designed and produced by Mr. Scott McPherson of the Swanson Center for Product Innovation. The PCB was designed with Cadence's PCB Design Studio, and manufactured at Advanced Circuits. A detailed mechanical drawing of the modulator and nozzle is presented in Figure 4, and the assembled system can be viewed in Figure 5.

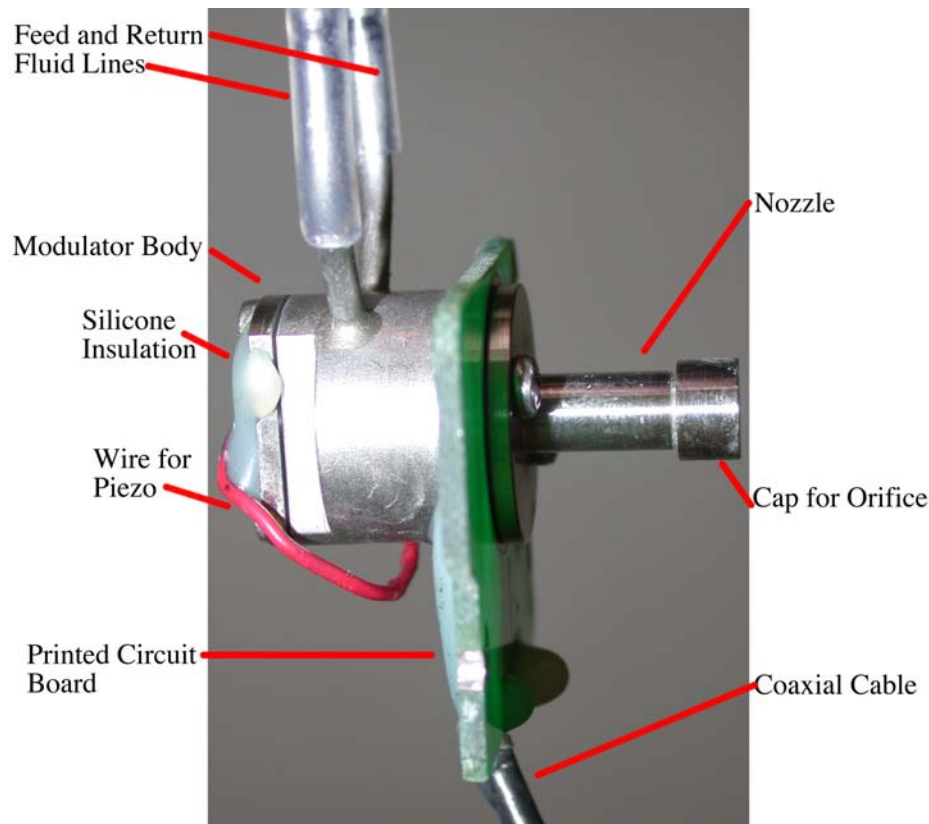


Figure 5: Assembled Fluid Ejection System

Fluid enters the feed line of the modulator at a typical pressure of 40 PSI (based on the Linx 6200 Printing System). The return line is either closed or restricted enough so that sufficient pressure exists at the orifice to allow fluid through it. If the return line is not restricted enough, there will not be enough pressure for fluid to exit through the orifice.

As fluid is continuously supplied, the piezo crystal is actuated by a sinusoid. Nominal values of this signal are 120-volts peak-to-peak at a frequency of 80 kHz (based on the Linx 6200 Printing System). This sinusoidal vibration is translated as a disturbance into the fluid in the modulator and effectively propagates along the fluid as it travels through the nozzle. When the fluid exits the nozzle, it is initially a solid stream, but the sinusoidal modulating wave imposed in the stream causes it to break up into individual droplets, as can be seen in Figure 6. In this picture, the stream is traveling from right to left.

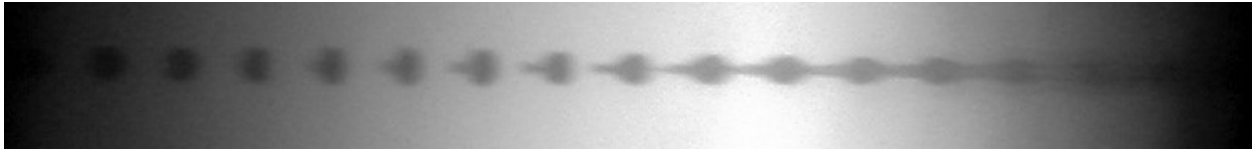


Figure 6: Example of Breakup Characteristic

3.0 EXPERIMENTAL SETUP AND PROCEDURE

Two different experimental systems were created and used to generate photographs of droplets. For each system, the fluid ejection system described in section 2.2 was used.

The first system consisted of a Linx 6200 printing system to supply modulation signals and fluid pressure to the fluid ejection system, and a Nikon CoolPix 995 digital camera fitted to an Edmund Scientific microscope with a 2X adapter was used to photograph the ink drops. All adjustability of the system variables was performed with the Linx 6200 printer.

The second system consisted of modulation circuitry based on the Linx 6200 printer, and a fluid pump of the same specifications as that found in the Linx 6200 printer, which allowed direct control of all system variables. A Sensicam high-speed camera was used to capture the resultant drops.

3.1 LINX PRINTER WITH NIKON CAMERA

The following text under subsection 3.1 describes; the experimental set up used to create ink droplets with the Linx 6200 Series CIJ printer, and the steps used to photograph them with the Nikon CoolPix 995 digital camera. Clear and concise descriptions of commands used on the Linx printer and the Nikon camera are given, but no attempt has been made to recreate the level of detail and reach covered by their respective manuals. For additional information or clarification of commands or items mentioned the reader of this document should refer to the printer[2] and camera[3] manuals.

3.1.1 Experimental Setup

To illuminate the ink stream, a PCB designed after the Linx MIDI CIJ print head (shown in Figure 2) was modified to hold an LED securely. This PCB had all material from the edge of the LED to where the nozzle is mounted removed. A charge tunnel was mounted into the PCB in order to hold the LED. Since it protruded above the LED, material from the charge tunnel on the topside of the board was removed to allow the most light possible from the LED to be in the field of view and to allow the camera to focus on the ink drops and not the charge tunnel. A yellow LED (Fairchild Semiconductor, Part Number MR3350) was then put into the charge tunnel, and connected to a DB-15 connector for use with the Linx 6200 printing system. Yellow was chosen because of its high contrast to the blue ink used by the system. Additionally, GE TSE397-C silicone rubber insulation was applied to the LED to protect it from caustic materials and to avoid any possibility of short-circuiting the anode and cathode of the LED.

The printed circuit board that provided a light source and the fluid ejection system were fitted to a block of Plexiglas. The light source and fluid ejection system were mounted in such a manner that the angle of ink ejection would be perpendicular to the angle of light projected from the LED. This can be seen in Figure 7.

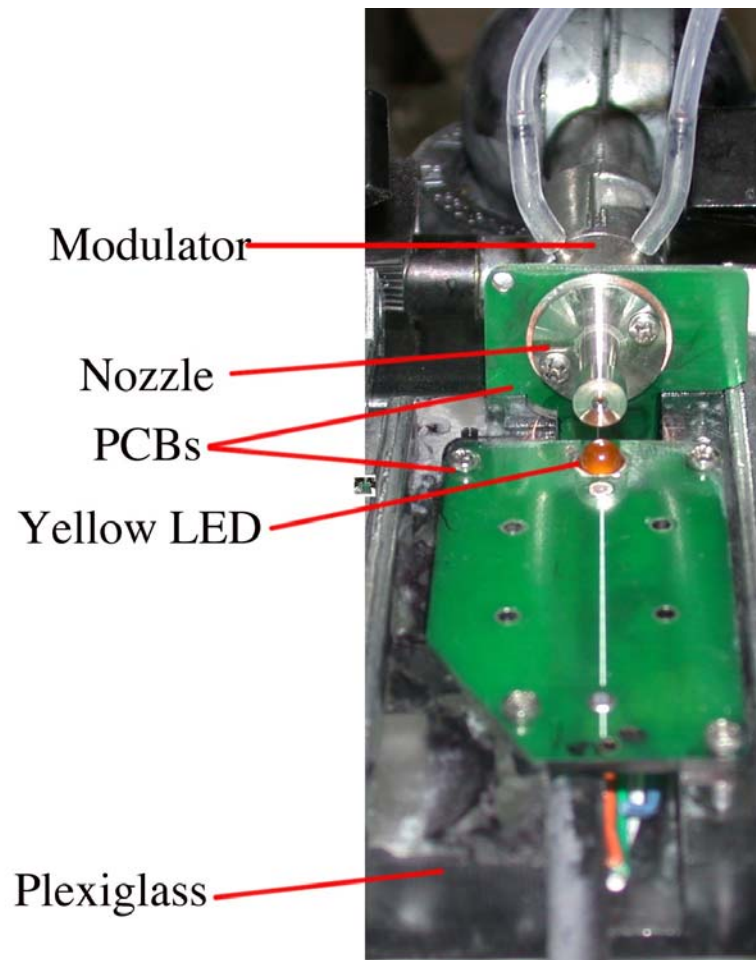


Figure 7: Fluid Ejection System and Lighting Held by Plexiglas

Photography to record the ink drops was achieved with a Nikon CoolPix 995 digital camera coupled to an Edmund Scientific microscope. Additional magnification was accomplished by using a 2X adapter as the coupler.

A circuit board holder (PanaVise model 315) supported by a standard base (PanaVise model 300) and a weighted base mount (PanaVise model 308) were used to hold the Plexiglas fixture into place. Orthogonality of the viewing surface to the microscope was achieved by using a level to adjust the PCB. The lens of the microscope was adjusted to be a safe distance from the nozzle so that the risk of getting ink on the lens would be minimized. This general concept is conveyed where the microscope, vise, level, and the device used to hold the LED and nozzle can be seen in Figure 8.

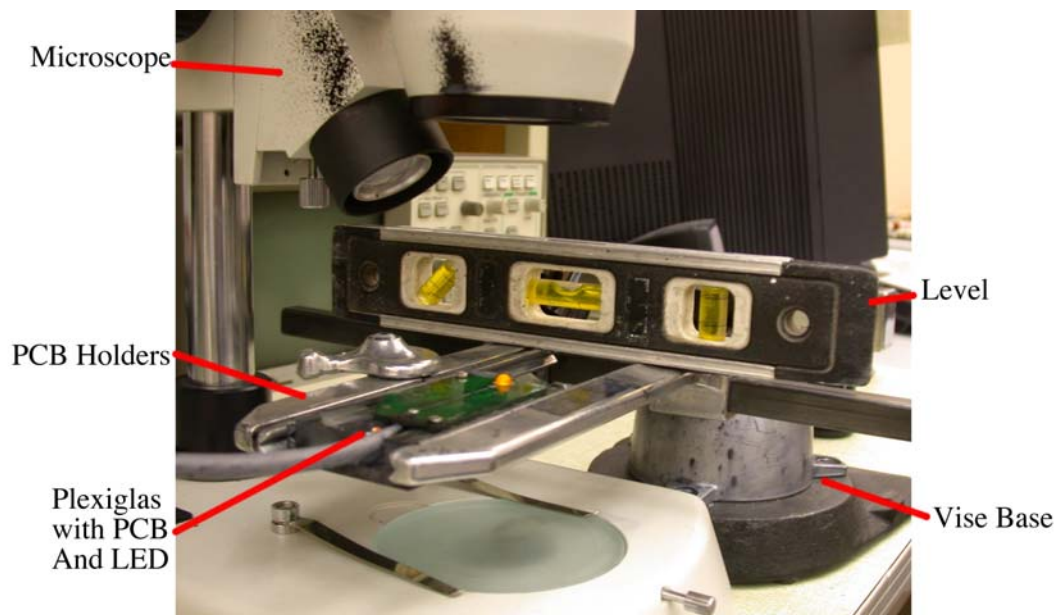


Figure 8: Adjusting PCB Holder

The nozzle, modulator, and LED were then connected to the Linx 6200 printing system, which supplied the modulation voltage, LED voltage, and fluid pressure. The system pulsed the LED synchronously with the modulation signal to make the drops appear to freeze in flight due to the stroboscopic effect. Blue MEK based ink was used as the fluid. Figure 9 displays the overall test environment.

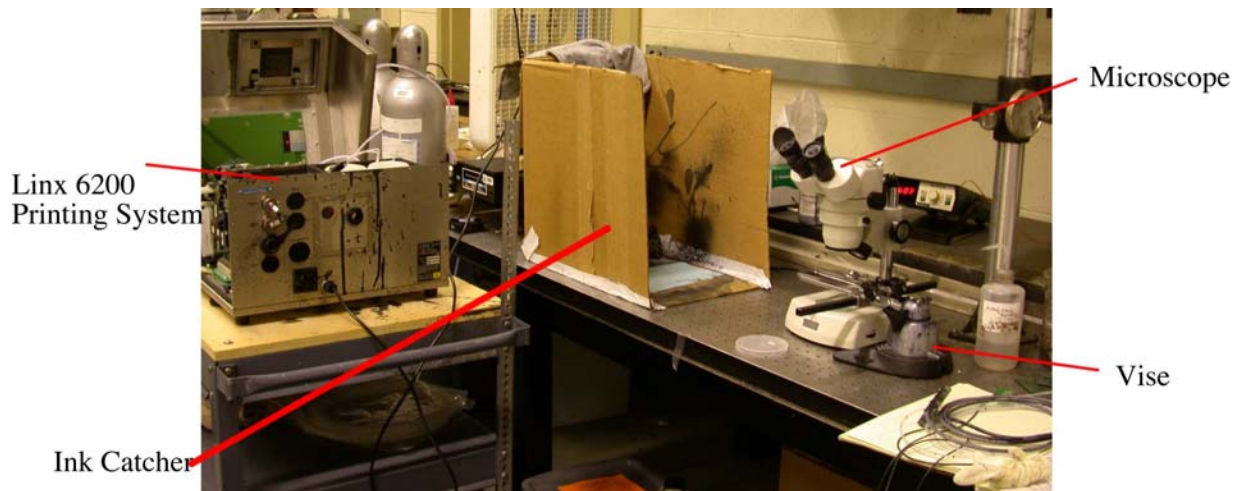


Figure 9: Linx Overall Test Environment

3.1.2 System Control and Adjusting Input Variables

3.1.2.1 Starting the Printer In order to start the fluid stream the “Quick Start Jet” feature was used. After initiation, the pump system went through several cycles before the stream appeared. To stop the fluid stream the “Stop Jet” feature was used. The system again went through several cycles as it purged the modulator before the jet was completely turned off. Table 1 illustrates the keystrokes and menu selections from the main menu needed to start and stop the jet. Keys or menu options are in bold, instructions are in *italic*. All control was performed with the QWERTY style keyboard on the printer.

Table 1: Starting and Stopping the Jet of the Linx 6200 Printer

Parameter	Steps
Start Jet	F4: Setup → Diagnostics → Quick Start Jet
Stop Jet	F4: Setup → Diagnostics → Stop Jet

3.1.2.2 Disabling Feedback Control It was found to be desirable to disable any system control variables that were not in use. Doing this allowed the use of the jet without the system automatically shutting down due to erroneous feedback that the printing system may have detected. Disabling feedback correction also maintained a steady stream since the system would not try to compensate for feedback variables that were not present. TABLE 2 illustrates the keystrokes and menu selections from the main menu needed to disable such parameters. Keys or menu options are in bold, instructions are in italic.

Table 2: Disabling Feedback Parameters of the Linx 6200 Printer

Parameter	Steps
Disable Phase Fault	F4: Setup → Diagnostics → Phase Fault → Enter → <i>Toggle left or right till OFF is seen</i> → Enter
Disable TOF Correction	F4: Setup → Diagnostics → TOF Correction → Enter → <i>Toggle left or right till OFF is seen</i> → Enter

3.1.2.3 Adjusting Pressure and Voltage The Linx 6200 printer allowed control of the pressure supplied to the fluid ejection system and the voltage magnitude supplied to the piezo crystal. Modulation frequency was not adjustable. Table 3 illustrates the keystrokes and menu selections from the main menu needed to adjust these variables. Keys or menu options are in bold, instructions are in italic.

Table 3: Pressure and Voltage Control for the Linx 6200 Printer

Parameter	Steps
Pressure	F4: Setup → Diagnostics → Set Pressure → Enter → <i>enter a value from 0 to 255</i> → Enter
Modulation Voltage	F4: Setup → Hardware Setup → Reference Modulation → Enter → <i>enter a numerical value for voltage</i> → Enter

While the entry for voltage represents the actual peak-to-peak voltage applied to the piezo crystal, the entry for pressure represents the decimal equivalent of an 8-bit code for the pressure. The pressure in PSI can be calculated by dividing the decimal value entered into the Linx 6200 printer by 3.9. This corresponds to a pressure range of 0 to 65.4 PSI.

$$\text{Pressure (PSI)} = \frac{\text{Decimal Entry}}{3.9}$$

3.1.2.4 Clearing Blockage In the event of the nozzle being blocked by foreign matter, the Linx 6200 printer has a “Clear Nozzle” feature. Access was obtained by using the following keystrokes: F4: Setup → Diagnostics → Clear Nozzle → Enter → Enter a number → Enter. After hitting “Enter,” the nozzle was held with a rag and drops of MEK were slowly placed on the orifice. Solvent was then drawn into the system in an effort to clear any foreign matter from the orifice. The number entered represented how many “Clear Nozzle” cycles were performed. Three cycles are what is suggested by the printer manual. If this procedure did not work, the nozzle was carefully disassembled, submerged in MEK for an extensive period then reassembled.

3.1.3 Acquiring Photographs

3.1.3.1 Adjusting Field of View Held by the vise, the Plexiglas apparatus was placed under the lens of the microscope. Since the LED is the source of light, it was brought into the field of view first by looking directly into the microscope to place it in the field of view of the microscope. Then, after attaching the camera to the microscope the LED was brought into the field of view of both the microscope and the camera by looking at the LED through the camera and adjusting the zoom settings of the camera, the settings of the microscope, and the LED position until it was visible. A thin wire or a pair of tweezers was used to probe the edges of the LED to make sure the entire LED was in the field of view. Doing so was essential for a reference scale. If it was not entirely in the field of view, the focal adjustment and the distance from the LED to the microscope lens were adjusted so that it was.

3.1.3.2 Focusing on the Ink Drops Once the LED was in the field of view, the ink stream was initiated as described in section 3.1.2.1. Caution was taken not to get ink on the microscope lens by covering it with paper while the jet was starting. After the jet was on, the focus was adjusted. The camera has automatic and manual focus settings. Automatic focus is the default setting for the camera, though manual focus was preferred. The camera was manually focused by turning the “Mode Dial” to “M” and holding down the button labeled “M-Focus” while turning the “Command Dial” until the ink drops were in focus. The optimum focal length was found to be 31 mm.

3.1.3.3 General Camera Settings Analysis of the ink drops was based on the distinction of the ink drops from the background. Color was therefore of no concern, and played no role in the analysis, and the camera saturation was set to black and white to give clearer images of higher quality. Pressing “Menu” on the camera while the “Mode Dial” was set to “M” turned on the shooting menu, where the “SATURATION” option was adjusted to “B&W” in the first shooting menu.

Images of the highest quality and size were desired so these options were set to their maximum. This was done by pressing the “Qual” button until “Hi” was visible, and turning the “Command Dial” while holding down the “Qual” button until no size indication was visible, indicating the largest picture size.

The camera was also adjusted for the use of the 2X adapter by pressing “Menu” with the “Mode Dial” set to “M” and selecting the “Telephoto 1” option for “LENS” in the first menu.

3.1.3.4 Shutter Speed and Aperture The best results were achieved by adjusting the shutter speed manually while the camera automatically adjusted the aperture. With the “Mode Dial” set to “M,” this feature was selected by pressing the “Mode” button and turning the command dial until mode “S” was selected. The shutter speed was then selected by turning the “Command Dial” until the desired shutter speed was obtained.

Photographs were taken with shutter speeds from 1/4 of a second to 1/1000 of a second. Any speed slower than 1/4 of a second became overexposed and anything faster than 1/1000 of a second was severely under-exposed.

With the camera adjusted to the desired settings, the “Shutter Release Button” was depressed to take photographs. Once all desired photographs were taken, the jet was stopped as described in section 3.1.2.1, and the photographs were downloaded from the camera for analysis.

3.2 CUSTOM SYSTEM WITH SENSICAM CAMERA

The following text under subsection 3.2 describes; the experimental set up used to create fluid droplets with the custom system, and the steps used to photograph them with the Sensicam High-speed camera. Clear and concise descriptions of commands used to control the camera are given, but no attempt has been made to recreate the level of detail and reach covered by the manual for it and its software. For additional information or clarification of commands or items mentioned the reader of this document should refer to the manuals for the camera[4] and its software[5].

This system was created because, while the Linx 6200 system was adequate for the basic requirements of producing and photographing ink droplets, it did not allow the control of modulation frequency. In addition, the system was cumbersome in its operation. The amount of feedback control often hampered experiments, and the cycles that the pump system went through when starting and stopping the ink stream made experiments very time consuming.

Fluids could not be readily changed in the Linx 6200 printer. Purging the system of all existing fluids and clearing all fluid handling components to avoid contaminating the new fluid would be required to try new fluids. The Linx 6200 printer was designed to print MEK based ink, and using new fluids would have risked damaging the system.

Lastly, photographing the droplets with the Nikon camera and microscope was considered insufficient. The limited field of view of the microscope and the small area illuminated by the LED proved very limiting in how much of the stream could be photographed. Individual droplets could not be captured, or a sequence of pictures that can be viewed as video could not be created with the Nikon camera's shutter speed. The stroboscopic effect and long shutter speed created images that consisted of multiple instances of time superimposed upon each other.

Because of all these factors, the custom system was developed to address and solve these issues.

3.2.1 Experimental Setup

The experimental set up using the Sensicam Camera to photograph fluid droplets created by the custom test apparatus consisted of five main components: a fluid pump to deliver liquid to the fluid ejection system, an amplifier to deliver a sinusoidal signal to the modulator, a lighting source, the camera, and a mounting system.

3.2.1.1 Fluid Pump A series 120 Electromagnetic Drive Pump manufactured by Micropump, Inc., was used to supply fluid to the fluid ejection system. This pump was selected because it matched the requirement to be able to create a fluid pressure of at least 40 PSI, which was the nominal pressure produced by the Linx 6200 Printing System.

For a fluid reservoir, a 125 mL Nalgene bottle was used. Holes were drilled and brass unions (Swagelok, part number B-200-6) were fitted to the lid of the bottle, which allowed tubing to be fitted to the bottle securely. Externally, tubing of equal lengths (approximately 3 inches) was connected to the unions. Internally, one union was fitted with a piece of tubing that extended to the bottom of the reservoir, while the other was fitted with a piece of tubing

approximately one half inch long. This was done with the intention of having feed and return lines for the reservoir to be used in conjunction with the feed and return lines of the fluid ejection system. Quick release couplings (Colder Products, SMC series) were also used to allow quick removal of the reservoir without loosening the brass unions. The tubing used was 0.0625-inch inner diameter, 0.125-inch outer diameter Teflon tubing. Figure 10 illustrates the reservoir.

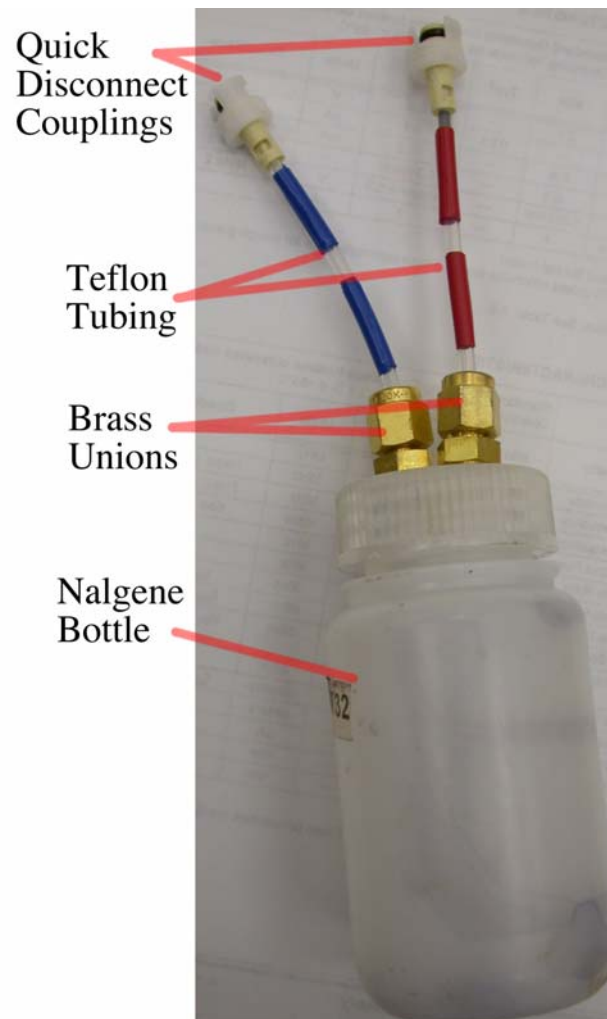
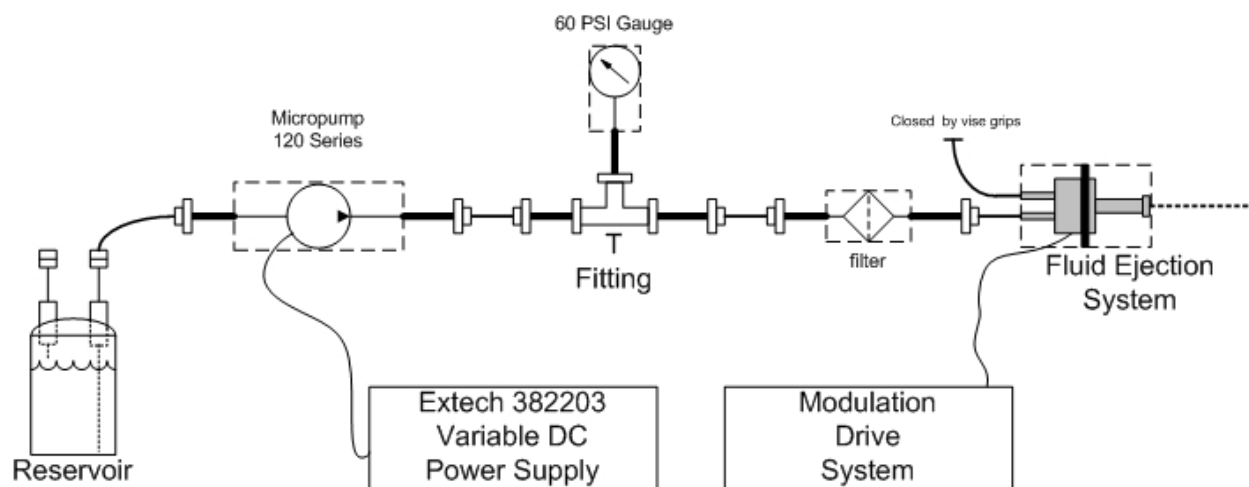


Figure 10: Fluid Reservoir

This reservoir was directly connected to the intake of the pump. The output of the pump was then fitted to a pressure gauge capable of reading up to 60 PSI (manufactured by Continental Precision Instruments). From the pressure gauge, tubing was connected to a filter, and then to one opening of the ink ejection system. Originally, it was attempted to run a return line from the nozzle back to the reservoir, but this did not create enough pressure to allow fluid through the orifice. To solve this, the return line of the ink ejection system was fitted with tubing, and this tubing was closed with vise grips so that all in coming fluid could only exit through the orifice. Distilled water was used as the liquid. For the path from the reservoir to the pump and then to the nozzle two different tubing diameters were used, and were connected with couplings.

A regulated variable DC power supply (Extech, model 382203) was directly connected to the pump in order to supply voltage to activate it, and vary the pressure. A schematic representation of the fluid connectivity is displayed in Figure 11. All components are represented, and except for connection lines inside hashed boxes, thin lines are used for sixteenth-inch inner diameter tubing, and thicker lines are used for eighth-inch inner diameter tubing. A photograph of the fluid pump, reservoir connection, and pressure gauge is seen in Figure 12.



KEY

□ 1/16" ID to 1/16" ID Coupling

□ 1/16" ID to 1/8" ID Coupling

□ 1/8" ID to 1/16" ID Coupling

— 1/16" Inner Diameter Tubing

— 1/8" Inner Diameter Tubing

Figure 11: Fluid Connectivity

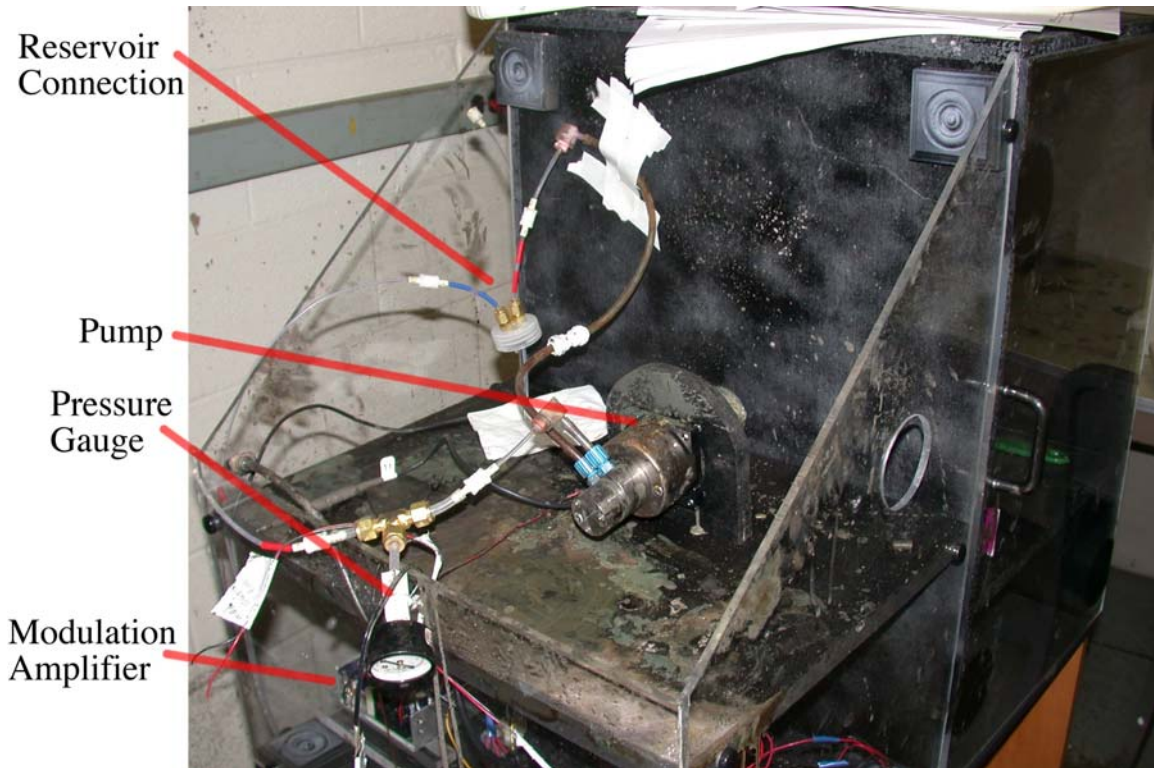


Figure 12: Fluid Pump

3.2.1.2 Modulation Amplifier A modulation amplifier was built based on schematics of the Linx 6200 printing system by Mr. Joshua Maina. This amplifier used a sinusoidal signal as an input, and created an amplified signal in phase with the input. For the input a function generator (Hewlett Packard 33120A) was connected directly to the input of the modulation amplifier. The output of the amplifier was first measured on an oscilloscope (Hewlett Packard 54602B) to verify the proper signal was being generated, and then connected to the RG174/U coaxial cable of the ink ejection system. Figure 13 gives a schematic of the circuit. The input is to the far left, and the output of the circuit is to the far right.

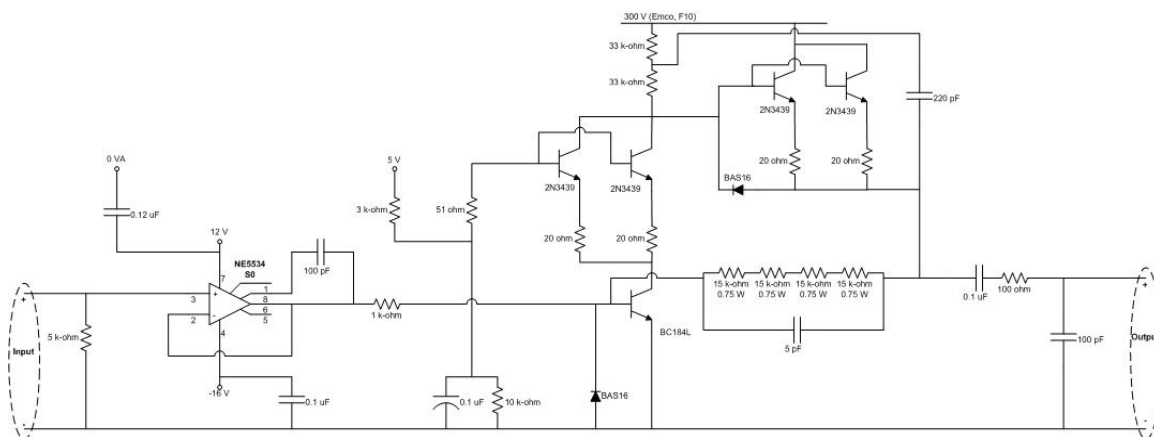


Figure 13: Modulation Circuitry

3.2.1.3 Light Source Attempts at using incandescent and fluorescent light sources were made, but these types of light sources proved to be inconsistent over their lifetime and difficult to work with due to their bulkiness and heat generation. In particular, disruption of the filament had noticeable effects on the quality of the incandescent light sources, and the fact that the lights were several times the size of the fluid ejection system made it difficult to illuminate the area millimeters away from the nozzle. LED light sources were then tried and proved to be much more useful due to their greater stability, the absence of heating characteristics found in incandescent sources, and their more manageable size. Efforts were made with both pre-manufactured LED arrays and individual LEDs. In each case a variable DC power supply (Hewlett Packard E3631A) was used to supply voltage to the LEDs, and held in place by a hobby vise (Wilton 63500/3VB Holding Device).

Yellow and red prefabricated LED clusters produced by Sunbrite LEDs (part numbers SSP-LXC1283S24 and SSP-LXC128624, respectively) were initially tried. Each cluster consisted of thirty two 0.5 mm LEDs in a circular array. While the individual LEDs produced enough light for the camera, the emitted light of each LED did not have a wide enough angle to

overlap each other and create the appearance of one solid light source. In addition, the spacing in between each LED was large enough to create too much non-illuminated area to be useful. Attempts at moving the light source farther away from the camera were made to give the light a greater chance to spread by the time it reached the lens, but the light intensity was not great enough when this was done.

Greater success was achieved with white LEDs, also produced by Sunbrite LEDs (part number SSP-01TWB9WB12). These LEDs were 10 mm in diameter, rated at 12-volts, and had an intensity of 11000 millicandela, which was the highest possible intensity found at minimum cost. Though designed for automotive applications they were easily adapted to the application of lighting the droplets of water. Their leads for the anode and cathode were easily accessible, and their wedge base designed for a specific mounting system proved very useful for holding the LEDs securely in the hobby vise. Four of these LEDs were connected in parallel, and held in a linear fashion with the hobby vise. At the cameras highest level of magnification, one LED would illuminate the field of view while lower levels of magnification would require more LEDs to illuminate the field of view. When close to the lens, the problem with seeing darkness between the LEDs was again present, but the amount of non-illuminated area was small enough to make the LEDs more useful than the prefabricated arrays. Moving the light source farther away from the camera so that the light would disperse was more effective with these LEDs than the prefabricated arrays. At farther distances from the lens enough intensity to illuminate the drops was produced while eliminating the darkness in between the LEDs. Figure 14 displays a front and side view of the LEDs held by the hobby vise.



Figure 14: Light Source, Front and Side Views

3.2.1.4 Camera System The camera system consisted of the Sensicam SVGA high-speed camera, a microscopic lens by Infinity Photo Optical Company, and a Dell Pentium based PC.

Exposure time was the main reason for choosing the Sensicam camera. Since the piezo crystal was activated at a rate of 80 kHz, the assumption has been made that there is a one-to-one correlation between frequency and the drop production rate. This may or may not be entirely true though because the system is pressurized within the modulation reservoir. Whether the effects of this pressure decrease or increase the rate of drop production has been greatly speculated. It was therefore necessary to take a conservative approach when selecting a camera and assume the drop rate was higher than 80 kHz. Not doing so could have risked purchasing an imaging system that was incapable of accurately photographing the creation of drops and given poor results. Using Nyquist's theorem that the sampling frequency must be greater than or equal

to twice the frequency of what is being sampled ($f_{\text{sample}} \geq 2f_{\text{process}}$) the speed requirement of the camera was determined. Rounding up to 100 kHz (to be conservative) created the requirement that the sampling rate be greater than or equal to 200 kFPS (frames per second). This translated to a shutter speed less than or equal to 5 μs . The Sensicam SVGA high-speed camera (produced by the Cooke Corporation) met this with a minimum exposure time of 100 ns.

Resolution was also an important factor. It was desired to have the greatest resolution possible to be able to capture as much of the drop breakup process as possible. The Sensicam SVGA had a resolution of 1280 x 1024 pixels. A higher resolution model did exist, but was not affordable with the budget that existed for this and related projects.

With an estimated drop size of no more than 200 microns, it was necessary to use a microscopic lens to see the droplets in detail. An InFocus Model KC Video Microscope system manufactured by Infinity Photo Optical Company was used to accomplish this. The system comprised of the main body lens, and four add on lenses – called objectives – to increase the magnification. This system was chosen for its magnification capabilities and simplicity. By directly attaching it to the camera, it was self supporting, did not require any additional mounting, and the different objectives were very easily changed.

The camera was controlled by a software package called CamWare (produced by the Cooke Corporation), which was installed on a Dell Dimension L733R Pentium based PC. A PCI board that was included with the camera was installed and provided the means necessary to directly connect the camera to the computer.

3.2.1.5 Mounting System A mounting system composed of Plexiglas and various vises was used to hold the camera, fluid ejection system, and lighting source in place, and was assembled by Mr. Stephen P. Heston. This mounting system with the computer was placed on a six-foot by three-foot table. A two inch thick sheet of Plexiglas measuring two-feet by 33.75 inches served as the base of the mounting system. Stability and control of the camera were achieved by a precision slide (Velmex, A1512K1-S1.5) mounted to a one-inch thick piece of Plexiglas, and secured to the Plexiglas base. The fluid ejection system was supported in a similar way to that of section 3.1.1 with the circuit board holder (PanaVise model 315) supported by a standard base (PanaVise model 300). Instead of a weighted base, the standard base was mounted to a half-inch

thick piece of Plexiglas and supported by a four-inch drill press vise (Columbian, model 69997). This allowed greater control over adjustment of the nozzle perpendicular to the line of sight of the camera so that various segments of the stream could be brought into view of the camera. The PCB that couples the modulator to the nozzle was held directly by the PanaVise circuit board holder. To give greater support for the PanaVise when its center of weight was not over the drill press vise, a 1.189-inch thick piece of Plexiglas was used. Free adjustment of the light source was achieved by allowing the hobby vise supporting the LEDs to move without restraint about the mounting system. Remaining components such as the computer and power supply were placed outside of the main Plexiglas base on the table. The fluid pump and modulation electronics were mounted on a separate utility cart. A detailed picture of the mounting for the camera and fluid ejection system is seen in Figure 15. In the middle of the photograph, the camera is aimed downward, while the nozzle held by the vise is positioned so the fluid stream will flow from right to left in the picture. The utility cart supporting the fluid pump and modulation circuitry can be seen in Figure 16. During operation the function generator driving the modulation circuitry was mounted on top of this utility cart.

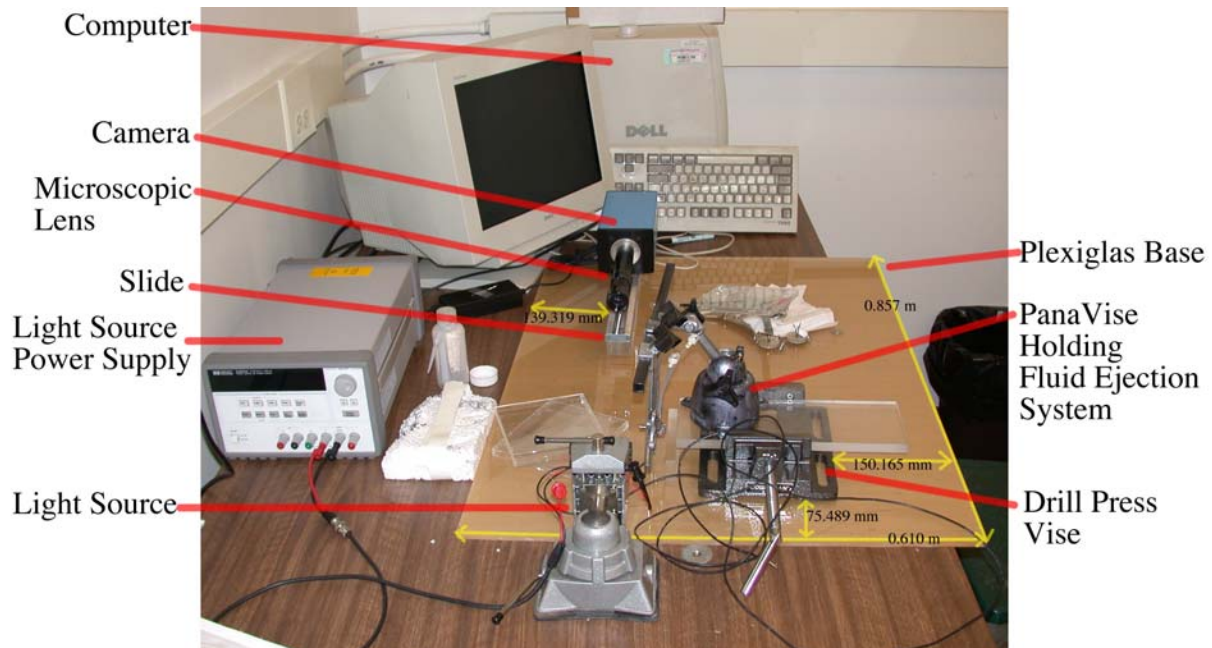


Figure 15: Overall Custom Setup

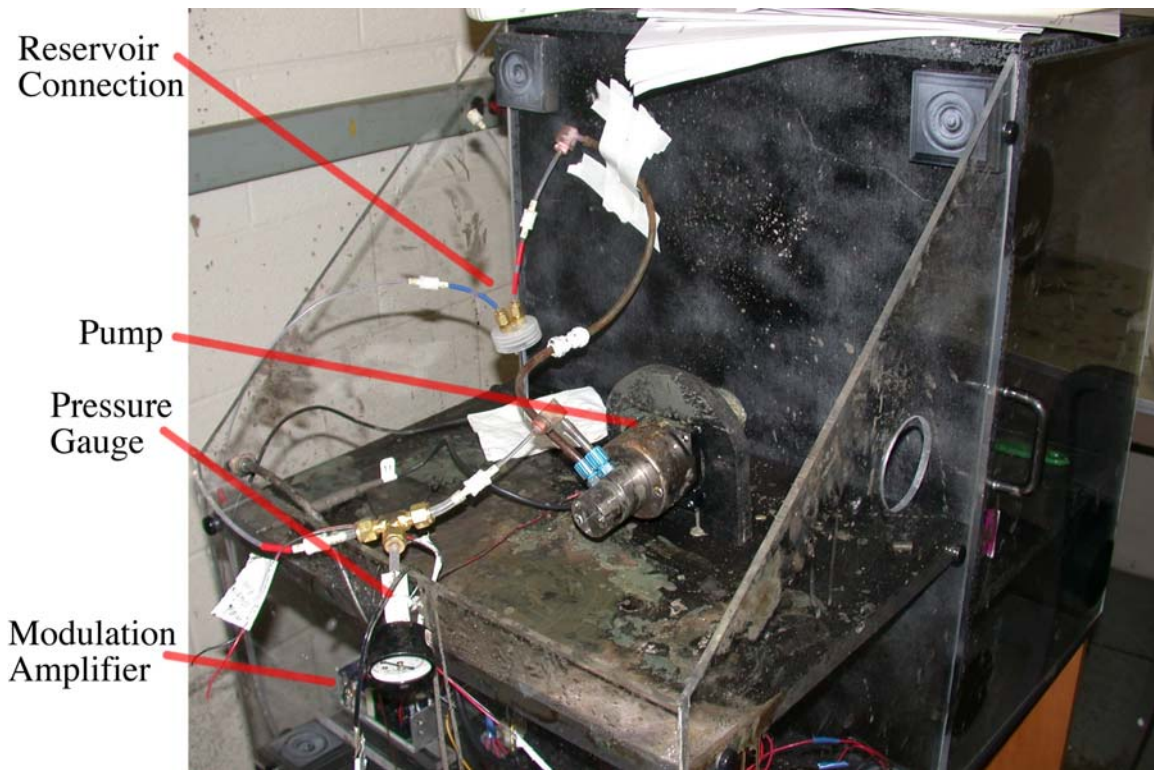


Figure 16: Fluid Pump and Modulation Mounting

3.2.2 System Control and Adjusting Input Variables

3.2.2.1 Pressure Pressure was adjusted by changing the voltage of the power supply that controlled the pump. Care was taken to adjust the voltage slowly while watching the pressure gauge so not to exceed the limits of the gauge. Voltage to the nearest half-volt was measured for various values of pressure, and the results are displayed in Table 4.

Table 4: Pressure and Corresponding Voltage

Pressure (PSI)	Voltage (Volts)
5	3.0
10	4.0
20	5.5
30	7.0
40	9.0
50	10.5
60	11.0

Limited accuracy existed in the pressure gauge. Due to instabilities in the system, the dial of the pressure gauge fluttered rapidly as the pressure was increased. Therefore, the pressure could only be estimated to the nearest PSI. Voltage was read directly from the gauge native to the power supply, which only had half-vote precision.

3.2.2.2 Modulation Voltage The modulation voltage was controlled by adjusting the input to the modulation amplifier with the function generator. Frequency is preserved from the input to the output, and the voltage is amplified approximately thirty to thirty-five times the original input voltage. Specific inputs necessary for outputs ranging from 50-volts peak-to-peak to 160-volts peak-to-peak are shown in Table 5. Voltages in excess of 160-volts peak-to-peak exceeded the capabilities of the modulation amplifier, causing the output to start clipping.

Table 5: Input/Output for Modulation Amplifier

Input (VPP)	Output (VPP)
1.46	50
1.78	60
2.10	70
2.41	80
2.70	90
3.02	100
3.36	110
3.89	120
4.33	130
4.70	140
5.08	150
5.50	160

3.2.2.3 Lighting To line up the LEDs within the field of view of the camera, the vise and LEDs were placed as close to the to the camera possible without touching the lens of the camera. With the LEDs on (12 volts) and the camera in “live preview”, the height and angles of the LEDs were adjusted while monitoring their effect on the camera’s view. If not high enough, shims were placed under the hobby vise. Once the desired height was obtained, the apparatus was carefully moved backward into the focal range so that each LED and the direction that the light was being projected could be seen. Positioning of each LED was confirmed by placing a thin object – such

as the tip of a pair of tweezers – in front of each LED and observing the output on the computer. The vise head was then adjusted so that the maximum light from the LED was entering the camera. The light was further optimized by adjusting each LED within the vise head to be shining directly into the camera and to be as close together as possible to minimize dark space between the LEDs.

3.2.3 Acquiring Photographs

The following subsections describe the best procedure found to photograph the droplets. Except for when recording images, the CamWare was in “Live Preview” mode so that the subject could be visible.

3.2.3.1 Adjust Light and Focus on Nozzle The desired objective lens was mounted for the level of magnification desired (IF1 having minimum magnification, IF4 having the maximum). As described in section 3.2.2.3, the light source was adjusted and positioned farther from the lens than the focal point. Once this was done, the nozzle was positioned in view of the camera so that the direction of the fluid stream would be perpendicular to the view of the camera. General focal adjustment was made by using the slide to move the camera closer to or farther from the nozzle. Fine focal adjustment was made with the “focusing ring” on the microscopic lens. The minimum and maximum focal distance achieved by adjusting the “focusing ring” for each objective is listed in Table 6.

Table 6: Focal Range for Each Objective Lens

Objective	Focal Range (mm)	
	Minimum	Maximum
IF1	241.3	802.6
IF2	196.5	624.8
IF3	159.9	291.3
IF4	62.1	80.3

Left-to-right (horizontal) adjustment of the nozzle in the field of view was accomplished by moving the PanaVise in the drill press vice. Up-and-down (vertical) adjustment was accomplished by moving the fluid ejection system in the jaws of the circuit board holders. Any angular adjustment was made by adjusting the means by which the circuit board holder was held by the PanaVise base. Care was taken to adjust the nozzle so that it was perpendicular with the view of the camera. Once the nozzle was in view of the camera, the fluid stream was initiated.

3.2.3.2 Start Liquid Stream and Adjust Viewed Section After getting the nozzle in view of the camera and the proper connections from the pump and modulation electronics to the fluid ejection system were completed, the fluid stream was initiated. This was done by adjusting the voltage supplied to the pump to produce the desired pressure, and by setting the modulation voltage to the desired values and connecting the modulation amplifier to the RG174/U coaxial cable. The stream was directed into an empty container so as to control the fluid.

The fluid stream and evidence of breakup characteristics were confirmed to be active by direct observation and by viewing the stream through the camera. If the nozzle appeared to be clogged, the same procedures to clear any blockage as in section 3.1.2.4 were followed.

Once a steady stream was produced, a photograph was taken with the nozzle in view to give a way to calculate a reference scale for the photographs. The desired section of the stream was brought into view by carefully loosening the drill press vise and slowly moving the PanaVise within the drill press vise until the desired section of the stream was in view. An adjustment to the position of the fluid ejection system in the circuit board holder was made if the stream happened to go above or below the field of view. When the desired section of the fluid stream was visible to the camera, the drill press vise was tightened, and fine focal adjustments were made.

3.2.3.3 Taking and Saving Photographs Control of exposure time, delay between photographs, and field of view selection were executed with the camera's software package, CamWare. Light intensity was primarily adjusted by varying the voltage supplied to the LEDs, though the option did exist within the camera software to adjust the light level.

The camera control window was used to adjust the exposure time and field of view of the camera. Individual exposure and delay times could be adjusted for ten photographs. For this thesis, delay times of zero-seconds were used. Live preview was required to be turned off while adjusting the exposure time and field of view. Since the fluid stream only occupied a small area in the overall viewing area, the camera control was also used to limit the photographing viewing area to a narrow horizontal band, though large enough to see the extents of the nozzle.

Picture quality was observed with the black-and-white window open and live preview on. The live preview compensated for the exposure time and displayed what the images looked like with the set light intensity and exposure time, and it was thus a very useful tool in monitoring the intensity of the light and its effect on image quality with the desired exposure time. Any desired changes to the light intensity were made at this point in time.

With all variables set as desired, and “Live Preview” turned off, photographs were recorded. Individual photographs were taken by selecting “Acquire Picture” from the “View” menu. Multiple images were taken by pressing the record button on the toolbar while the camera control menu was visible. Once taken, the images could be viewed in the black-and-white window. In play back mode it was necessary to adjust the options so that only the ten images were viewed.

Saving individual pictures was done by selecting “Export” from the “Image” menu. Multiple images were saved by selecting “Export Recorder” from the “Image” menu.

4.0 DROPLET ANALYSIS

Using two separate software packages, methods were developed to analyze the droplets. The first program used was Matlab, a commonly used program in engineering for signal processing, image processing, and general analysis. The second is ImageJ, a Java based, freely distributed image analysis program with many of the same features as Matlab. Though not as powerful and flexible as Matlab, it is presented here in the event the CIJ designer does not have access to Matlab, which comes at a cost.

For the analysis, two photographs from the experimental setup using the Linx Printer and Nikon camera, and one set of ten photographs from the custom system and Sensicam camera are used in this chapter. The first picture used here that was taken with the Nikon camera was recorded with a shutter speed of 1/8 second, and can be seen in Figure 17. Figure 18 displays the second picture, which was taken with a shutter speed of 1/250 second. In each photograph the fluid ejection system was supplied with 120 VPP modulation voltage and 40 PSI of pressure. The ink stream is traveling from right to left in these photographs. The group of Sensicam photographs show the ink stream generated under nominal conditions, and each photograph was exposed for 4 μ s. An example of the Sensicam photograph can be seen in Figure 19. Objective IF3 was used in these photographs, and the droplets are traveling from left to right.

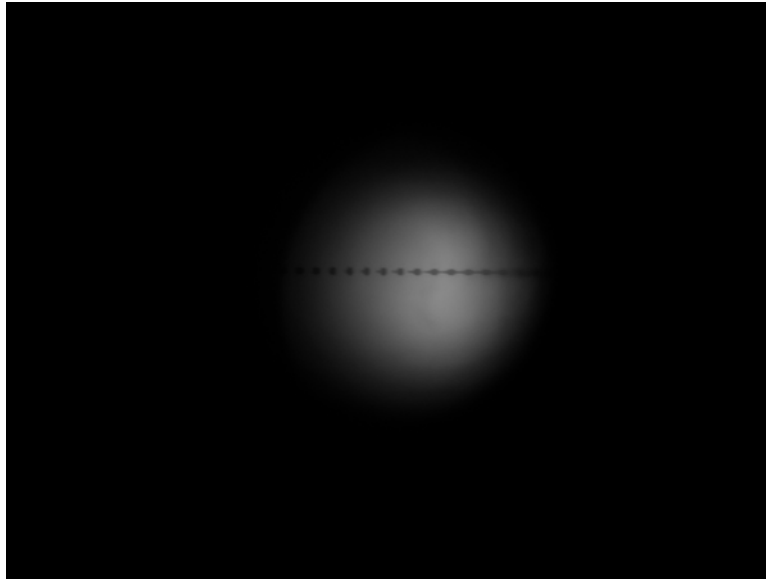


Figure 17: Linx with Nikon Test Set Up, 1/8 Second Exposure

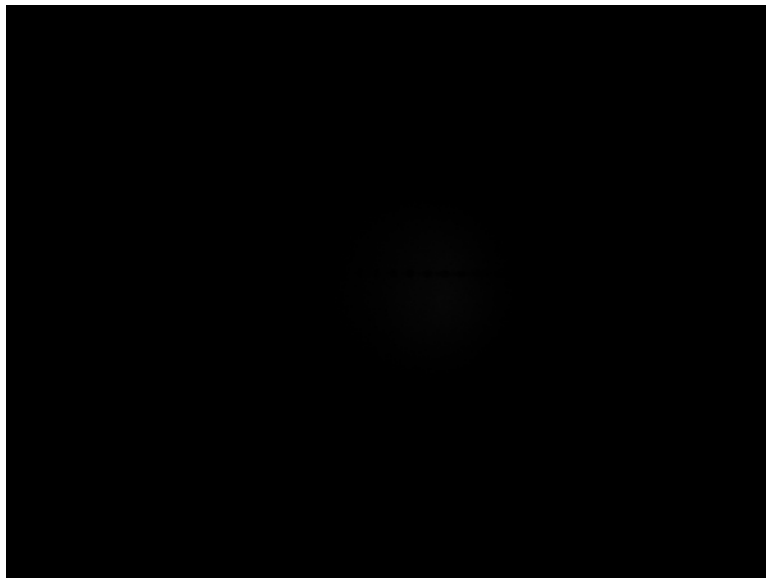


Figure 18: Linx with Nikon Test Set Up, 1/250 Second Exposure



Figure 19: Sensicam Photograph, 4 Microsecond Exposure

As was done previously in this thesis, the commands used in the software packages are given, but no attempt is made to give a complete description of how to operate the software. The reader is advised to consult the documentation associated with the software packages for elaboration on information concerning any of the items discussed.

Relevant Matlab commands are given for each subsection in this chapter. Complete Matlab scripts that were used can be found in the Appendix.

4.1 MAKING MEASUREMENTS

For the analysis it was necessary to measure such features as the nozzle diameter, the stream diameters, and droplet diameters. Because this is so common throughout all aspects of this chapter, this section is presented here to describe in detail the steps used to make the measurements.

4.1.1 Matlab

With the desired figure in view, the command “pixval” was entered in the command window. This created a display in the bottom left corner of the active figure window. To measure a linear dimension the cursor was placed at beginning of the feature to be measured and the left mouse button was depressed. Without releasing the left mouse button the cursor was then placed at the end of the feature to be measured. The distance in pixels between the two points was read from the display in the bottom left corner and recorded. The line drawn by this process is only active while the left mouse button is constantly depressed.

4.1.2 ImageJ

From the ImageJ toolbar the “straight line selections” tool was selected. To measure the linear dimension the cursor was placed at the beginning of the feature to be measured, the left mouse button was depressed, and the cursor was then placed at the end of the feature, similar to what was done in Matlab. Unlike Matlab, the line was still active when the left mouse button was released. This allowed the “zoom” tool to enlarge the start and end points of the measured feature, and control the placement of the beginning and end of the measuring line as precisely as possible. The measurement was then made by “Measure” from the “Analyze” menu, which displayed the result in a separate window. Additionally, the counter-clockwise rotational angle of the line could be noted on the ImageJ toolbar when moving one end of the line.

4.2 PRELIMINARY PROCESSING

4.2.1 Loading the Image

4.2.1.1 Matlab Images were loaded using the command “imread”.

4.2.1.2 ImageJ ImageJ did not require any special scripting, and files were loaded by selecting “Open...” from the “File” menu.

4.2.2 Calculating Reference Scale

In order to calculate droplet parameters in terms of useful units a reference length was necessary in the photographs. For the images taken with the Nikon camera, the diameter of the LED (5000 μm) was used because it was the only distinctive measurable feature in these photographs. The images taken with the Sensicam camera though had two features that were recognizable and measurable. The first is the outside diameter of the nozzle (6350 μm), and the second is the diameter of the fluid stream immediately after leaving the nozzle, which was assumed to be the same diameter of the orifice (60 μm). These two feature measurements gave two reference scales, and both were used in the measurements made. In both Matlab and ImageJ, the appropriate dimension was measured in terms of pixels, and this information was then used to convert all measurements from pixels to μm . Since the Linx photograph taken at 1/250 seconds does not have any observable features due to the low level of exposure, the reference scale from 1/8 second photograph was used. The test setup was not disturbed in between these photographs, and consequently this is acceptable. The specific steps used in each program are described below.

4.2.2.1 Matlab The original image was brought into view using “imshow.” The desired reference feature was then measured, and this measurement was then used to create the conversion factor for the image. A script to load the image, display it, and turn on the interactive display was written, and is given in the Appendix.

4.2.2.2 ImageJ With the image to be analyzed in view, the reference feature was measured. This measurement was recorded and used to calculate the reference scale. Automatic conversion was available with the “Set Scale” option found under the “Analyze” menu. If a measurement was active, the length in pixels was automatically entered in the appropriate placeholder. By entering the known length of the reference object, giving the units, and pressing “Ok,” all future measurements would be given in terms of the actual length.

4.2.2.3 Reference Scale Values The calculated reference scales for each photograph are listed in Table 7. In this table, the calculated number of pixels found for each reference feature is given, and the corresponding reference scale that was calculated.

Table 7: Calculated Reference Scale Versions

Program	Photograph	Reference Feature	Pixels	Scale (pixels/ μm)
Matlab	Linx	LED (5000 μm)	701.93	0.14
	Sensicam	Nozzle (6350 μm)	733.426	0.12
		Stream (60 μm)	8.03	0.13
ImageJ	Linx	LED (5000 μm)	686.00	0.14
	Sensicam	Nozzle (6350 μm)	729.04	0.12
		Stream (60 μm)	8.00	0.13

4.2.3 Increasing Image Clarity

Despite the ink drops being clearly distinguishable from the background in many of the photographs, it was necessary to take steps to increase their definition. This is because while the drops were visible overall, their edges may not have been clearly defined, making accurate measurements of feature sizes difficult. Cases also existed where the droplets appeared to not exist at all due to poor exposure. Processing of the images was therefore necessary to produce reliable results. The same approach to improving image clarity was applied in both Matlab and ImageJ. First, histogram equalization was applied. Then, if possible, an edge detection algorithm was used.

In an 8-bit grey scale image, there are 256 levels of grey intensity, ranging from solid black (0) to solid white (255). In cases where the intensity levels are concentrated over a very small band, image definition was greatly improved by applying histogram equalization, which spread the intensity levels over all possible values. Though applied to all images, this was especially useful in images that were underexposed due to inadequate lighting for the shutter speed used.

Edge detection algorithms were available in both software packages. These algorithms look for sharp changes in contrast. What the algorithm calculates to be an edge is highlighted in white, and the intermediate areas are left black. For the analysis, the actual boundary was interpreted to be the center of the white line drawn by the algorithm. The Sobel method was the only edge detection available in ImageJ. Thus, the same method was used in Matlab for the purpose of direct comparison.

The specific commands in Matlab and ImageJ used to utilize these features are listed below. Other commands specific to each program that were found to be useful in increasing image clarity are mentioned as well.

4.2.3.1 Matlab For reference, the histogram of the image was viewed by using the command “imhist.” Histogram equalization was then performed by using the command “histeq.” In some cases the contrast of the equalized image would still be low, so the “imadjust” command was used to increase the contrast. The effect of histogram equalization can be seen in Figure 20. For the original image, it can be seen that the grey intensities are concentrated over one fifth of the spectrum. After performing histogram equalization, the intensities are distributed over the entire range, and parts of the image that appeared to be unexposed are now visible.

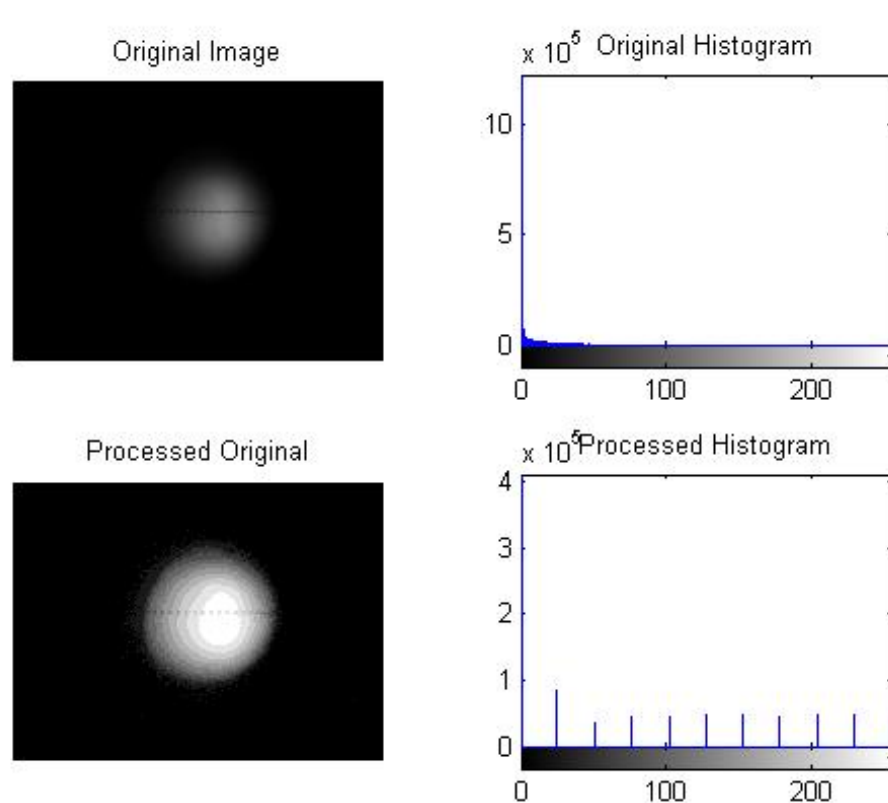


Figure 20: Matlab Effect of Histogram Equalization

The “edge” function was then used utilizing the Sobel method in order to give clearly defined edges. An example of this is shown in Figure 21. The default threshold proved to be to be inadequate for the processing of these images. Table 8 displays the thresholds that were found to give the best result, where “graythresh” calculates a threshold level used in the detection based on the image used.

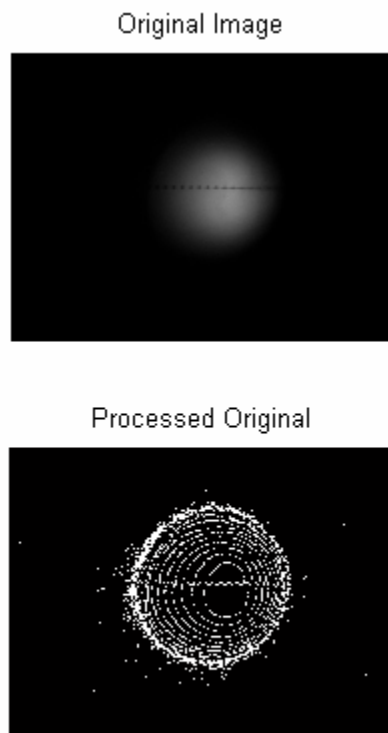


Figure 21: Matlab Edge Detection

Table 8: Edge Detection Threshold Levels

Photograph	Level
Linx, 1/8 s Shutter	$\text{graythresh}(\langle \text{variable name} \rangle) * 0.001$
Linx, 1/250 s Shutter	$\text{graythresh}(\langle \text{variable name} \rangle) * 0.36$
Sensicam	$\text{graythresh}(\langle \text{variable name} \rangle) * 0.17$

4.2.3.2 ImageJ To view the histogram for an image “Histogram” under the “Analyze” menu was selected. Two methods existed to perform histogram equalization. One was to use “Enhance Contrast” from the “Process Menu.” With this tool, the “Equalize Histogram” was performed. In some cases, this option appeared to remove pixels from the edges of the droplets. When this occurred “Adjust... Brightness/Contrast...” under the “Image” menu was selected. The auto button was found to adjust the spread of the intensity levels just as well. Both methods were tried in order to determine which was more appropriate on a case-by-case basis. Examples of the effects of histogram equalization are shown in Figure 22 and Figure 23. In each figure, the top half is the photograph before histogram equalization, and the bottom half is the same image after equalization.

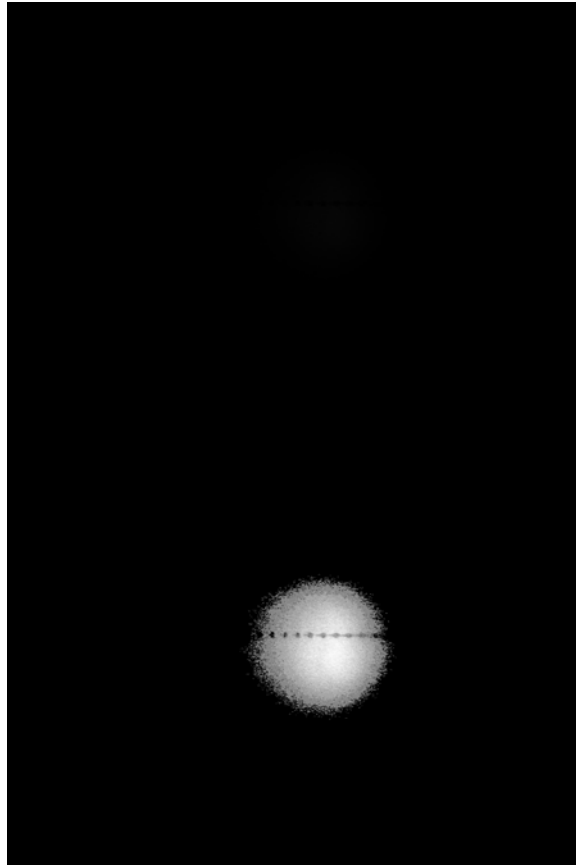


Figure 22: ImageJ Histogram Equalization on Nikon Photograph

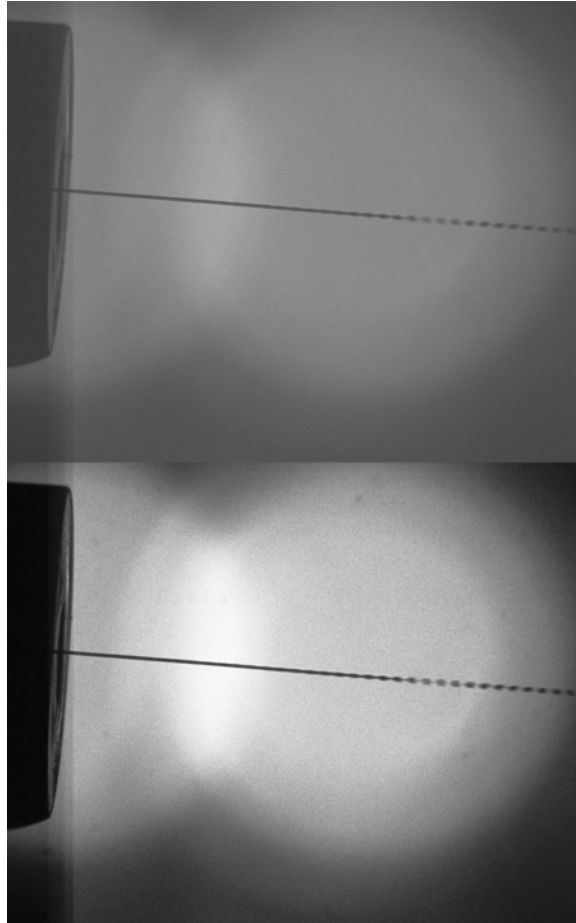


Figure 23: ImageJ Histogram Equalization on Sensicam Photograph

After performing histogram equalization, the edges were automatically detected by selecting “Find Edges” under the “Process” menu. In some cases, background noise would be high enough that this feature would not give positive results. Results of edge detection are shown in Figure 24 and Figure 25. In each figure, the top half is the photograph before histogram equalization and edge detection, and the bottom half is the same image after histogram equalization and edge detection have been applied.

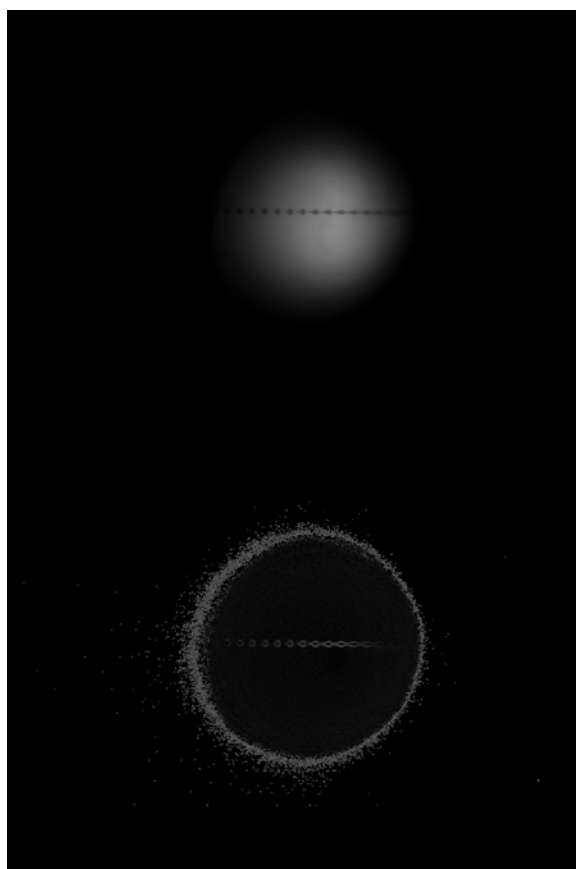


Figure 24: ImageJ Edge Detection on Nikon Photograph

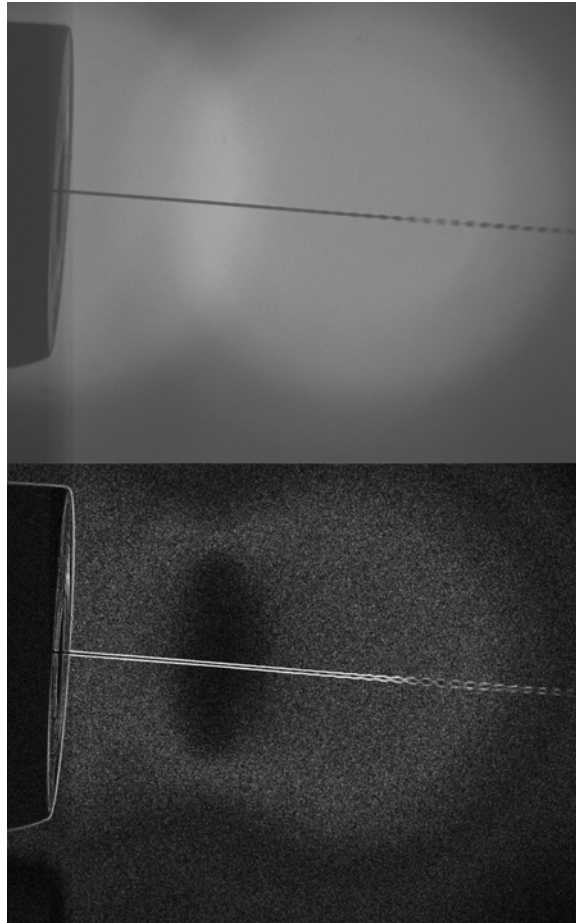


Figure 25: ImageJ Edge Detection on Sensicam Photograph

Cropping the photographs from the Linx printer and Nikon Camera experiments proved to add some convenience. These photographs contained a lot of unexposed area that did not contribute any information. To do this one of the selection tools was used to enclose the area to be kept, “Crop” was selected from the “Image” menu, and the undesired portions of the image were removed.

In some cases, where a low level of noise existed in the background, the “Subtract Background” feature from the “Process” menu was used. This effectively set the background to solid white, while maintaining the droplets in the foreground. In cases where the background had too much noise and the drops were not distinguished enough from the background, this feature was highly counterproductive.

4.3 VELOCITY

A method to measure velocity was developed for the images recorded by the Sensicam camera since it produced multiple photographs where a droplet could be tracked over the course of the ten-photograph sequence. The images recorded by the Nikon camera are still images, and do not have any representation of movement. Regardless of this, a method to estimate the velocity of the droplets in the Nikon photographs is presented as well.

Despite the Sensicam photographs having extremely short exposure times, the fact that the droplet is in motion creates some level of blurring in the photograph as it moves during the exposure time. As mentioned in Section 3.2.3.3, images for this thesis were taken with a delay of zero-seconds between exposures. It is thus expected that the end position of a droplet in one photograph will be the same as the start position of that same droplet in the subsequent photograph. This concept is related in Figure 26.

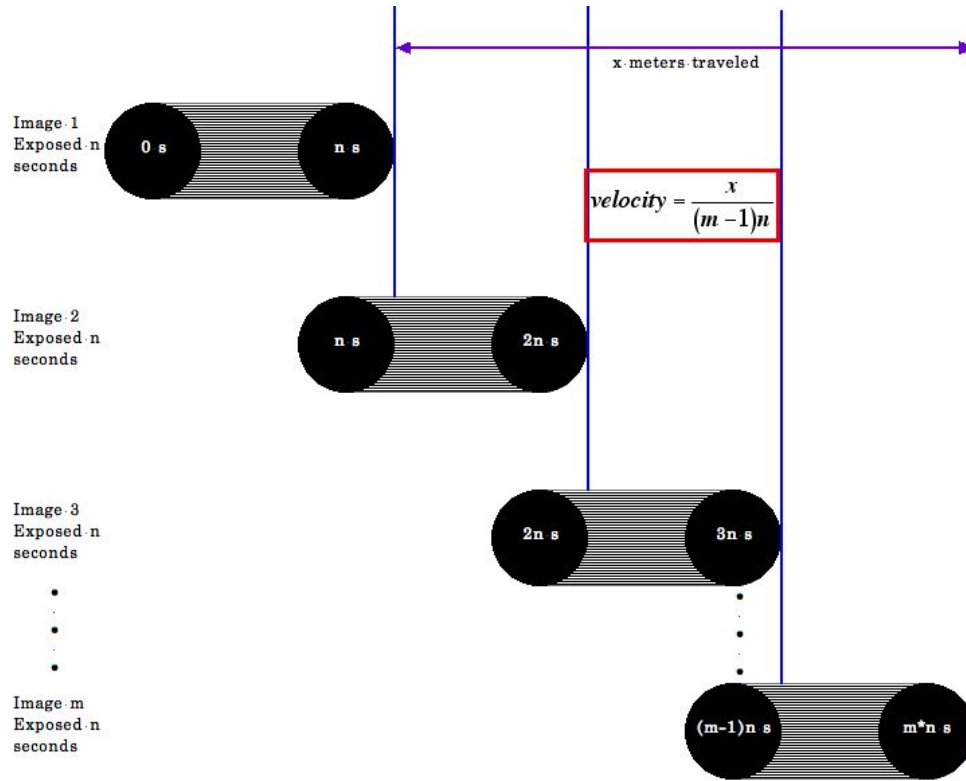


Figure 26: Illustration of Velocity Calculation

From this interpretation, the distance from the right most edge of the droplet in a photograph to the far right edge of the droplet in next photograph corresponds to the total distance traveled during the time the second photograph was exposed. If m photographs are used, each with an exposure time of n seconds, the velocity will be equal to measured distance, x , in meters over the course of the m photographs divided by $(m-1)n$ seconds.

$$velocity = \frac{x}{(m-1)n}$$

For the Linx photographs, the velocity was estimated by assuming the drops are being produced at a rate of 80 kHz. With this assumption the number of droplets in a given distance were measured, and used to calculate the velocity.

$$velocity = \frac{drops}{s} \times \frac{m}{drops}$$

The steps necessary to calculate the two velocities with these approaches are given below.

4.3.1 Matlab

In Matlab, one of the images from the Sensicam series was initially loaded with “imread.” After turning on “pixval” in the command window, the minimum x and y coordinates and height and width of the area to be cropped were selected. The goal was to remove all aspects of the picture except the ink stream. These values were used to write a script that read all the images of the series, cropped them identically, and then assigned them to a large matrix. This script can be found in the appendix. This matrix resulted in a single picture comprised of all the cropped segments stacked on top of each other. White space was added to the bottom to have an area to measure the distance with the method described above. Desired processing from section 4.2.3 was then applied to this image. It was found that too much noise existed to perform edge detection, so all analysis was performed with just histogram equalization applied. This resultant image can be seen in Figure 27. The first image in the series is at the top of the figure, and the last image in the series is at the bottom.

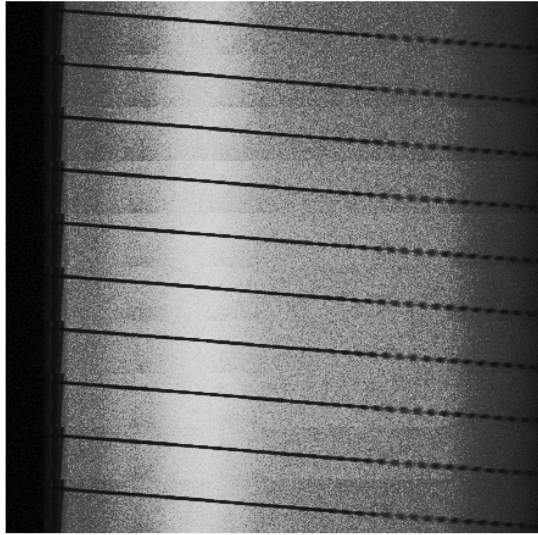


Figure 27: Matlab Velocity Measurement

An “insert line” tool existed in the figure window, and was used to draw lines from droplet to droplet for the measurements. The drawback found was that when the zoom tools are used, the lines drawn do not follow the zoom, and therefore, they do not scale with the picture or move with the location they were initially drawn. Using this “insert line” tool, lines were drawn vertically along the rightmost edge of the droplet to be followed. When located in the next picture, this process was repeated until all visible occurrences of the drop were traced. Because the angle of these lines was not displayed, they were estimated to be parallel to the best ability of the eye. The distance of the droplet’s path over the course of photographs was measured in pixels by measuring the distance from the first line to the last, and converted to the appropriate units. Since information on the angle of the line was not given the measurement was taken parallel to the stream.

To calculate the velocity of the droplets in the Nikon photographs, the far right edge of one droplet to the far right edge of a later drop was measured. Counting the number drops along this distance the velocity was calculated with the equation presented at the beginning of this section.

4.3.2 ImageJ

In ImageJ, each photograph of a series or selection of photographs from the series to be analyzed was opened. The height of the image area containing the stream was estimated, and “New...” was selected from the file menu. A name was selected for the new image, and dimensions were entered. The width was chosen to be the same as the original photographs (1280 pixels) and the height was chosen to be the estimated height of the area containing the stream multiplied by the number of photographs to be used plus 500 pixels to make sure enough area was available. Following these steps generated a blank image on which to copy and paste segments from the series of photographs.

Once the new image was created, the first photograph of the series was selected making sure the entire photograph was viewable. Using the rectangular selection tool, the area containing just the stream was selected. To ensure precise alignment with other segments the left and right edges of the box were positioned to the farthest extents of the image. With the desired area selected, “Copy” was selected from the “Edit” menu, and inserted into the new image by choosing “Paste” from the “Edit” menu. The pasted image was then dragged and dropped to top of the new image. Using the arrow keys on the keyboard and viewing the ImageJ tool bar, the pasted image was moved to coordinates $(X, Y) = (0, 0)$.

Once the first image was in place, the second image was copied and pasted in the same manner. When in the new image, it was dragged and dropped directly below the first image, and moved using the arrow keys until the x coordinate of the image was zero. This process was continuously repeated until selections from all images in the series were included in the new image.

After performing any desired processing as described in section 4.3 and setting the reference scale for the picture, a drop was selected to follow through the sequence. Using the straight-line selection tool a line was drawn from the right most edge of the droplet to the bottom most section of the overall image. Consistency and accuracy were maintained by viewing the ImageJ tool bar to make sure the angle of the line was 270 degrees. “Draw” was selected from the “Edit” menu once it was determined a straight line was successfully drawn against the right most edge of the droplet. The position of the droplet being investigated in the next photograph was determined, and a line was drawn against its right most edge to the bottom of the image in the same manner. After repeating the procedure for each photograph, the horizontal distance was then measured from left most line drawn to the right most line drawn.

It was also necessary to account for any angle in the stream. By using the straight line selection tool to trace the path of the stream, the counter clock wise angle around the axis was read from the ImageJ tool bar. Subtracting this angle from 360 degrees gave the clockwise angle and was used to calculate the actual distance by dividing the measured distance by the cosine of this angle.

$$\text{actual distance} = \frac{\text{measured distance}}{\cos(\text{clock wise angle})}$$

With the actual distance across the series of photographs measured, the velocity was calculated by using the equation shown at the beginning of this section.

Figure 28 shows an image created with the series of Sensicam photographs used to measure the velocity of a droplet. Each photograph is exposed for 4 μs , and the droplet is traveling from left to right.

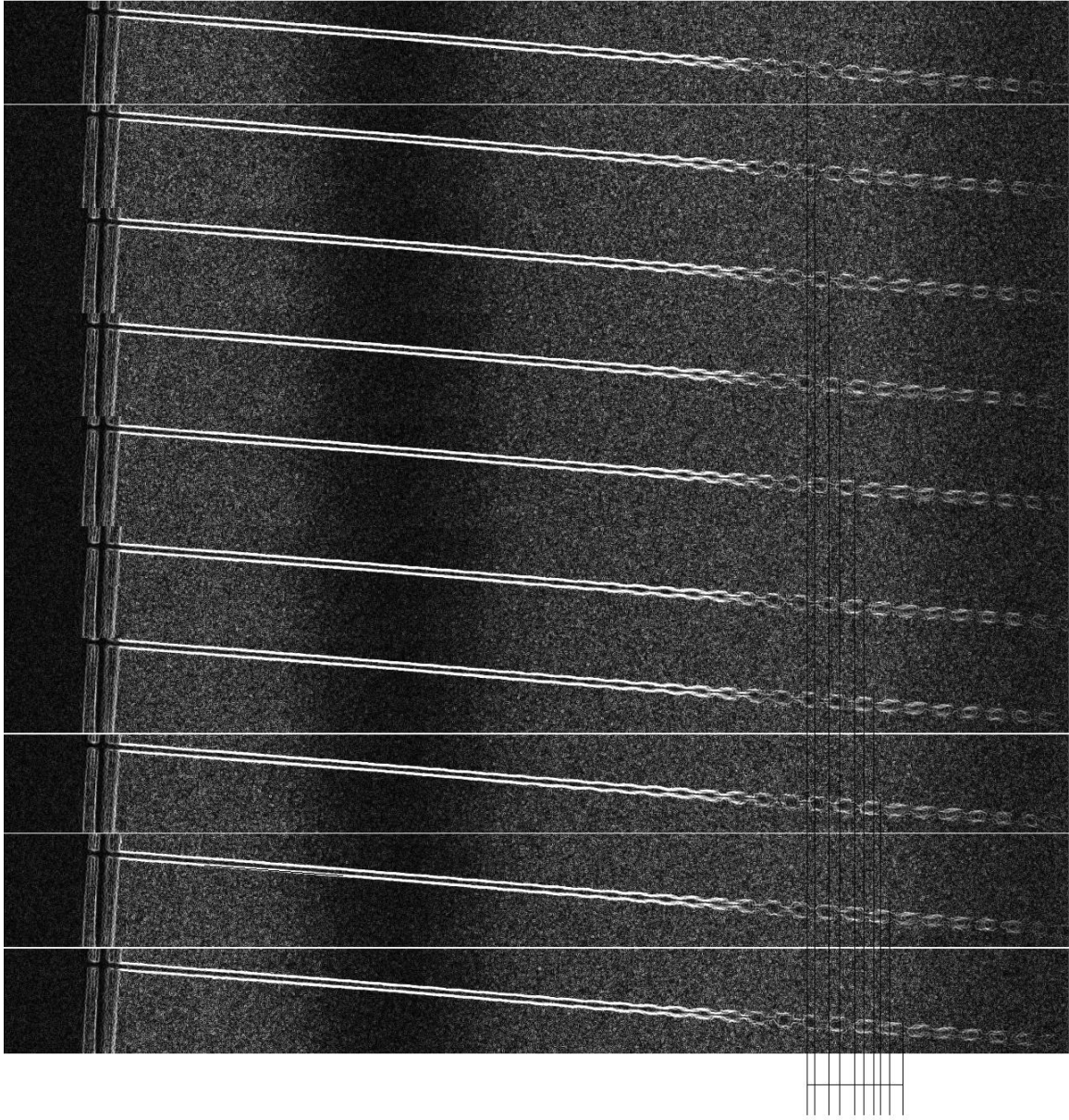


Figure 28: ImageJ Velocity Measurement

To calculate the velocity of the droplets in the Nikon photographs, the far right edge of one droplet to the far right edge of a later drop was measured. Counting the number drops along this distance the velocity was calculated with the equation presented at the beginning of this section.

4.3.3 Velocity Results

The calculated velocities of the droplets in the Sensicam images are given in Table 9. All aspects needed to calculate the velocity are shown.

Table 9: Sensicam Photograph Calculated Velocity

Program	Scale (pixels/μm)	Distance (x)	Photographs (m)	Exposure Time (n)	Velocity
Matlab	0.12	918.33 μm	10	4 μs	25.51 m/s
	0.13	847.69 μm	10	4 μs	23.55 m/s
ImageJ	0.12	952.47 μm	10	4 μs	26.46 m/s
	0.13	879.20 μm	10	4 μs	24.42 m/s

Table 10 displays the velocity calculated for the Nikon photographs under the assumption that the droplets are being produced at a rate of eighty-thousand drops per second.

Table 10: Nikon Photograph Calculated Velocity

Program	Assumed Frequency	Distance	Droplets	Velocity
Matlab	80 kHz	1911.93 μm	6	25.49 m/s
ImageJ	80 kHz	1921.43 μm	6	25.62 m/s

4.4 VOLUME

The following assumptions were used in creating a method to calculate the volume of the droplets:

- The ink drop can be described as an ellipsoid, which is defined in Cartesian coordinates as

$$\frac{x^2}{a^2} + \frac{y^2}{b^2} + \frac{z^2}{c^2} = 1$$

and has an volume of

$$Volume = \frac{4}{3} \pi abc$$

where a , b , and c , are the radii in the x , y , and z axes, respectively

- The only force on the drop is due to its separation from the fluid stream after the surface tension has been overcome, and this force distributes itself equally throughout the droplet after a very short time interval
- The effects of gravity and wind resistance are negligible

With respect to the photographs, the x -axis was treated as the horizontal axis, the z -axis as the vertical axis, and the y -axis as the third dimension into and out of the picture. Since only two of the three axes were measurable in the photographs, a method to estimate the y -axis was necessary. By the second and third assumptions as the radius of the droplet fluctuated along the x -axis, the radii along the z -axis and y -axis would change equally, and no other forces existed that would make them different from each other. Therefore, the volume could be calculated by measuring the horizontal and vertical radii (a and c , respectively) of the droplet and using:

$$Volume = \frac{4}{3} \pi a c^2$$

For the photographs produced by the Sensicam camera, the extents of the droplet were measured. However, due to the effects of blurring mentioned in section 4.3, this measurement was not the true diameter. This was accounted for by using the velocity measurements from Section 4.3 to calculate how far the droplet traveled over the time of the exposure, and subtracting this distance from the initial measurement.

$$actual\ diameter = (initial\ measured\ diameter\ with\ blur) - distance\ traveled\ during\ exposure$$

Even though the velocity was calculated for the pictures produced by the Nikon camera, the longer exposure times of these pictures did not make this approach practical. Volumes for the Nikon photographs therefore did not take into account the effects of blurring in the photograph.

4.4.1 Matlab

After processing the images, the droplet to be measured was enlarged using the “zoom” tool in the figure window. The horizontal and vertical diameters were then measured as described in section 4.1. These dimensions were then converted to radii and used to calculate the volume of the droplet.

4.4.2 ImageJ

After the images were processed, and the reference scale was set, the droplet to be measured was enlarged by using the “zoom” tool. The horizontal diameter and the vertical diameter were measured, and the results were read for the results menu. These diameters were then halved to find the radii, and these radii were used to calculate the volume of the droplets.

4.4.3 Volume Results

A sample of 10 droplets from the Sensicam photographs was used to calculate average radii and volumes. Next, 12 droplets from the two Linx photographs were used to calculate the same. The resultant calculated volumes are given in Table 11. In this table, the mean and standard deviation for each radii and the volume are given. The columns displaying the mean values are highlighted in grey because they may be of more immediate interest.

Table 11: Volume Calculations

Program	Photograph	Scale	Mean <i>a</i> (μm)	<i>a</i> Standard Dev.	Mean <i>c</i> (μm)	<i>c</i> Standard Dev.	Mean Vol. (pico liters)	Vol. Standard Dev.
Matlab	Linx	0.14	75.53	19.13	69.19	7.41	1551.78	578.30
	Sensicam	0.12	52.86	9.79	65.40	7.33	982.47	323.29
		0.13	44.87	9.03	60.37	6.76	772.67	254.26
ImageJ	Linx	0.14	69.35	66.37	66.37	7.05	1292.98	355.01
	Sensicam	0.12	35.86	8.54	58.88	6.53	534.64	189.42
		0.13	33.11	7.88	54.35	6.02	420.63	149.00

4.5 DROP RATE

Knowing the velocity of the ink droplets and the number of droplets over a specific range, the drop production rate can be calculated.

$$\frac{\text{drops}}{\text{second}} = \frac{\text{meters}}{\text{second}} \times \frac{\text{drops}}{\text{meter}}$$

Because velocity was not directly calculated for the Nikon photographs, and drop rate was assumed, the drop rate cannot be calculated for these images. In the Sensicam series used to calculate volume, the number of droplets was measured over a distance, and the corresponding drop breakup rate was calculated.

The above procedures were performed to measure the distance over a series of drops. These measurements with the velocities calculated in section 4.3 were used to find the drop rates, and the results are seen in Table 12.

Table 12: Calculated Drop Rates

Program	Scale	Velocity	Drops	Distance	Drop Rate
Matlab	0.12	25.51 m/s	10	2645.18	96.44 drops/s
	0.13	23.55 m/s	10	2441.71	96.24 drops/s
Sensicam	0.12	26.46 m/s	10	2658.18	99.54 drops/s
	0.13	24.42 m/s	10	2453.70	99.52 drops/s

4.6 SPACING

Calculation of spacing was formulated to measure the distance from the center of one drop to the center of an adjacent drop. To calculate the spacing, the distance between the outside edges of two adjacent droplets was calculated. The horizontal diameters of each droplet were then measured, and the radii of each were subtracted from edge-to-edge distance. Blurring, as in previous section, could have been considered the Sensicam photographs, but since this would have equally shifted the center of each droplet the final results would have been the same.

A sample of 12 droplet distances in the Sensicam images, and a sample of 11 droplet distances in the Nikon photographs were measured. The average droplet spacing and standard deviations were calculated, and are given in Table 13.

Table 13: Spacing Results

Program	Photograph	Scale	Mean Droplet Spacing (μm)	Standard Deviation
Matlab	Linx	0.14	316.65	13.66
	Sensicam	0.12	264.19	17.84
		0.13	243.87	16.47
ImageJ	Linx	0.14	322.09	9.16
	Sensicam	0.12	267.32	9.04
		0.13	246.75	8.34

5.0 DISCUSSION

5.1 GENERAL PROCEDURES

In general, the procedures presented are consistent from program to program, and system to system. When comparing the results found using Matlab of a particular photograph to those found using ImageJ, the linear measurements made typically differ by less than 10 μm . This corresponds to less than one and a half pixels difference. The largest difference in linear measurement is seen in Table 9, where the measurements over ten droplets differs by at most 35 μm , which corresponds to four pixels. Such a difference is slight, and easily contributed to human error. Since the diameter measurements were made by drawing the cursor over the extents of the droplets by hand, an inconsistency in picking beginning and end points for the droplets could have easily been made. Differences could also be contributed to any difference in the algorithms used by each program. This is very plausible considering the threshold level for edge detection was specified in Matlab but not ImageJ.

Consistency is also seen when comparing the results of the Linx printer with the custom experimental setup. The measurements for velocity and spacing are very similar between the two systems, and linear dimensions differ overall by at most four pixels as well. Despite running each system at the same levels of pressure and voltage, precision could have been compromised due to a piece of equipment being out of calibration. In addition, a difference is naturally expected between the two systems because ink was used with the Linx printer, and water was used with the custom experimental setup. Differences between the fluid characteristics such as density and viscosity are expected to have an impact on the results, despite how similar they may be. Humidity and temperature at the time of the experiments may have played a role as well. Any error in measurement could have then amplified these system dissimilarities.

5.2 VELOCITY AND DROP RATE

In chapter four two items draw immediate attention. First, despite being produced by very similar processes, the volumes of the measured droplets in the Linx photographs are much larger than those recorded by the Sensicam camera. Second, the modulator was excited by a frequency of 80 kHz, but the calculated drop rate was found to be on the order of 96 - 99 kHz.

It is immediately observed that for the volume calculations the average vertical radius, c , is fairly consistent across all measurements, differing by no more than 15 μm . However, the average horizontal radius, a , of the Linx system is calculated to be much different than that of the droplets recorded by the Sensicam camera, at points more than twice the size. It also makes little sense that the droplet would be so non-spherical, regardless of any transient the droplet may be experiencing. While some difference due to natural differences in the fluids, closer results are anticipated due to the similarity of results of other observable factors. This error in calculation is contributed to the adjustment to the horizontal diameter made by calculating the distance traveled with the calculated velocity and subtracting that distance from the measured diameter. Not applying the same method to the Linx images additionally amplifies any differences when trying to draw a comparison. A better comparison can be made by looking at the radii and volumes without accounting for velocity in Table 14.

Table 14: Volume Calculations without Taking Into Account Velocity

Program	Photograph	Scale	Mean <i>a</i> (μm)	<i>a</i> Standard Dev.	Mean <i>c</i> (μm)	<i>c</i> Standard Dev.	Mean Vol. (pico liters)	Vol. Standard Dev.
Matlab	Linx	0.14	75.53	19.13	69.19	7.41	1551.78	578.30
	Sensicam	0.12	103.88	9.79	65.40	7.33	1906.78	511.61
		0.13	95.89	9.03	60.37	6.76	1499.74	402.39
ImageJ	Linx	0.14	69.35	66.37	66.37	7.05	1292.98	355.01
	Sensicam	0.12	88.78	8.54	58.88	6.53	1311.72	338.06
		0.13	81.95	7.88	54.35	6.02	1031.70	265.90

It can be seen that without accounting for velocity, the average volumes are much more similar, though a notable difference does still exist. The issue of the horizontal and vertical measurements being very much different from each other still exists as well. Now instead of the horizontal radii being much smaller than the vertical radii, it is now much larger. By assuming the droplets are to be observed as spherical, it can be said that the initial calculations show the velocity as being calculated too high. The volumes and horizontal radii found without accounting for velocity then indicate that velocity does in fact need to be considered when interpreting the photographs.

By itself, the calculation of a drop rate on the order of 96 - 99 kHz may raise questions as to whether the system is linear. Many factors may have contributed to an error in the drop rate calculation though, many that have already been mentioned in the previous discussion of general procedures and volume. One additional factor may be the velocity, which is proportional to the

drop rate. When calculating velocities in this thesis, the time used to divide the distanced traveled was the sum of nine exposure times. With zero delay in between exposures, no other time needed to be accounted for. Despite the camera being completely electrically controlled (that is, no mechanical shutter), the concept of having zero delay is questionable. If an inherent delay exists, the time used in the calculation of velocity is smaller than what it should be, which would have led to a velocity that was calculated to be too high than what it actually is, which directly creates a calculation of a drop rate that is also higher than what it actually is.

These observations on volume and drop rate lead to the conclusion that the velocity was calculated too high, but for reasons that are uncontrollable with the current methods and processes. Regardless, the velocities that were calculated are very close to the velocity estimation made before this thesis was written, which is approximately 21 meters per second.

5.3 REFERENCE SCALE

Error in the calculated results could have resulted from any error in the references scales. For the Linx photographs, the edges of the LED are not distinct, so as the light from the LED gradually fades to complete black, the actual edge of the LED needed to be approximated. This could have very easily led to a miscalculation of reference scale.

For the Sensicam photographs, using the diameter of the fluid stream has many factors to consider. In the analysis, it was assumed the diameter of this stream was the diameter of the orifice. The diameter of the orifice being a manufactured component is produced within a certain level of tolerance, and therefore may not be exactly 60 μm . In addition, the exact fluid dynamics, and their effect on the diameter of the stream as it leaves the orifice is unknown.

Using the outside diameter of the nozzle has some ambiguity as well. Although it is static, the surface of the nozzle is visible, indicating that the stream is not fully perpendicular to the camera despite the best efforts to do so. With this angle, droplets in one portion of the stream may be closer to the camera than in other portions, adding some inaccuracy to the measurements.

5.4 LIGHTING

The LEDs as a light source proved to have a great influence on the quality of the photographs. If too close to the focal point of the camera the different features of the LED could be distinguished, and many voids exists, where droplets were not exposed. Moving the LEDs farther away from the focal point reduced the voids, and made the light appear to be more evenly distributed. The LEDs overall had a very granular effect on the image quality, which made the detected edges not very distinct in appearance.

An extreme example of the LEDs positioned too close to the camera's focal point, exposing the voids in between them is seen in Figure 29. An example of the LEDs being positioned farther away from the focal point can be seen in Figure 30. In this figure, the area in the middle where the LED is most intense has excellent contrast despite the noise, but towards the fringes of LED, the light intensity is less brilliant, more noise is present, and droplets are poorly recognized, making their analysis somewhat questionable. Figure 30 also shows how even at farther distances the circularity of the LED creates a circular gradient of light.

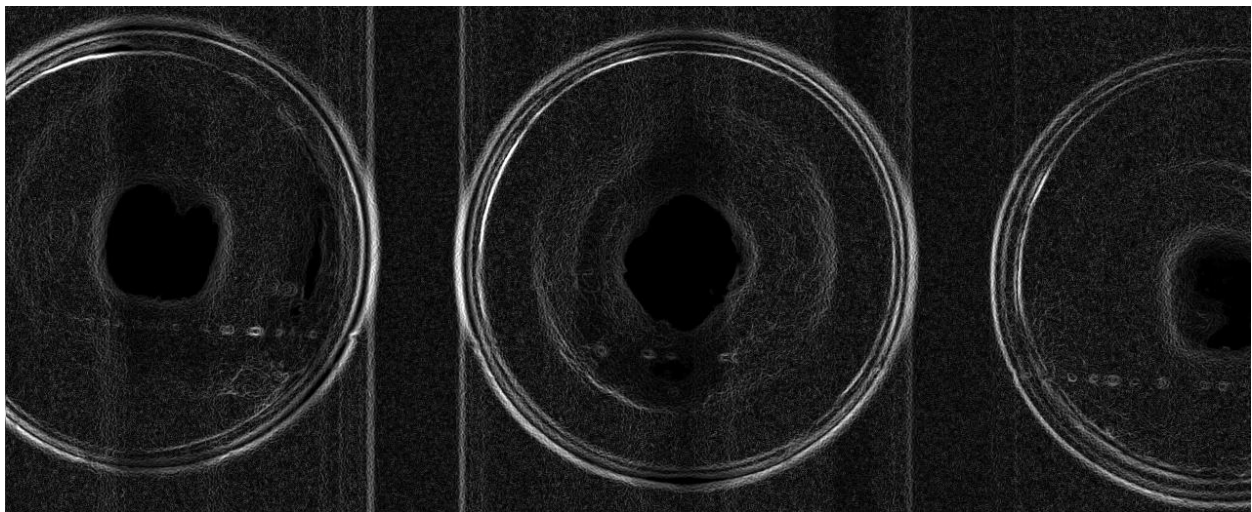


Figure 29: Sensicam Photograph, LEDs Very Close

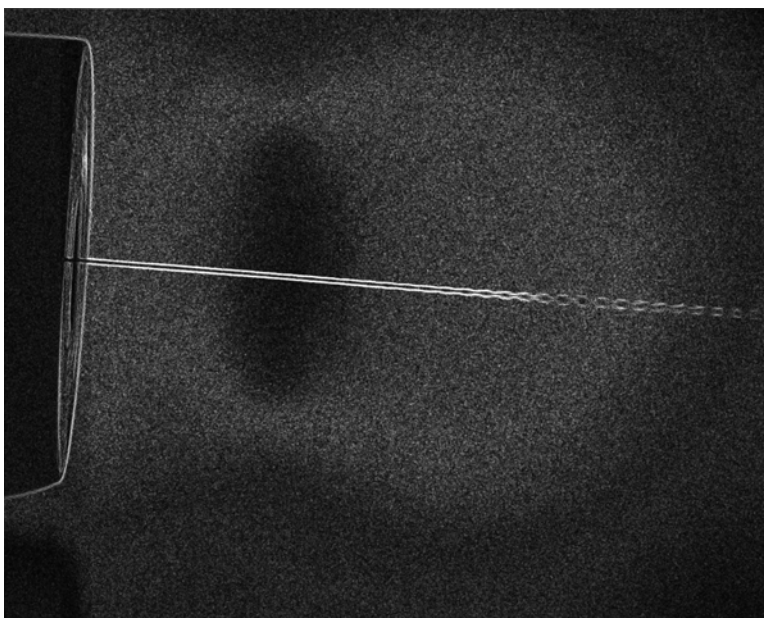


Figure 30: Sensicam Photograph, LEDs Far Away

6.0 CONCLUSIONS

The work presented in this document has created the framework to construct and use a system to produce droplets from a CIJ system, to record the droplets photographically, and to analyze the images to deduce information about the droplets. While the resources of many people were used to accomplish this, the efforts of myself specifically include:

- Creating specifications and sourcing of components not currently available
- Utilization of all available resources to accomplish the desired goal
- Development of practices that best utilize the experimental systems
- Selection of software to analyze the photographs
- Development of techniques to analyze the photographs with the selected software
- Analysis of results

Pressure, modulation voltage, and modulation frequency are controllable, and methods to evaluate droplet volume, drop spacing, and droplet velocity, and drop production rate were successfully developed. The experimental arrangements described allow one to develop a test environment from either limited or extensive resources. Enough information has been given to create such a test environment, to trouble shoot or enhance a current working system, or trouble shoot or operate the specific test units described here which are found at the University of Pittsburgh. The inherent error that exists in the test environment resulted in an error of approximately 20% from the anticipated values.

While some error exists in the measurements and calculations presented, the observations presented to argue that the actual velocity is lower than the calculated velocity shows that the procedures and methods presented demonstrate a level of accuracy within range of previously measured and theoretical values. Any inaccuracies can be contributed to measurement error, environment effects on the fluids, and inherent levels of precision that may be lacking in the experimental apparatuses used.

Many improvements could be added to future evolutions of the described systems. The vises used in the custom system, though sturdy, are by no means precision instruments. Holding devices custom tooled for the purpose of holding and adjusting the positions of the fluid ejection system, lighting source, and camera would greatly enhance the accuracy, reliability, and precision of the system.

In addition, a lighting source of greater intensity and planar luminescence will aid greatly in the ability to analyze the recorded photographs. Higher levels of light intensity will allow greater contrast at higher exposure speeds, making it easier to analyze droplets at greater velocities. Background image noise will be drastically reduced with lighting that is more evenly spread. Many of the photographs presented in this thesis show the negative effects the curved light from the LEDs imposed upon the image backgrounds making processing of them often difficult.

Different methods for defining a reference scale would be of great benefit as well. The methods described here require a feature such as the LED or nozzle to be in view of the photograph, which limits the extent that the droplets can be magnified and scaled. Smaller reference objects that can be positioned the same distance as the stream, and in view of the camera, will allow greater magnification and greater precisions in measurement.

Even without these additions, the systems and methods described will prove to be adequate in the evaluation of a CIJ system when designing it for either the application of printing, or new research endeavors.

APPENDIX

A.1 REFERENCE SCALE

```
close all, clear
```

```
%Load and display original image
```

```
I = imread('DSCN1928.JPG');
```

```
figure(1)
```

```
imshow(I)
```

```
title('Original Image')
```

```
pixval
```

A.2 PROCESS IMAGES

```
%for thesis
```

```
close all, clear
```

```
%Load and display original image
```

```
I = imread('DSCN1934.JPG');
```

```
figure(1)
```

```
imshow(I)
```

```
title('Original Image')
```

```
%converts RGB to grey, if necessary, be sure to adjust subsequent variables
```

```
I2 = RGB2GRAY(I)
```

```
%Display Histogram
```

```
figure(2)
```

```
imhist(I2)
```

```
%Perform Histogram Equalization, and display new image
```

```
I3 = histeq(I2);
```

```
figure(3)
```

```
imshow(I3)
```

```

title('Original Image With Histogram Equalization')

%adjust contrast
I4 = imadjust(I3, stretchlim(I3), [0 1]);
figure(4), imshow(I4), title('contrast adjusted')

%Perform Edge Detection
A=.36; %threshold multiplier
BW = edge(I4, 'sobel',graythresh(I4)*A);
figure(5)
imshow(BW)
title('Detected Edges')

%using strel and imdilate to dilate the image
se90 = strel('line', 3, 90);
se0 = strel('line', 3, 0);

BWsdil = imdilate(BW, [se90 se0]);
figure(6), imshow(BWsdil), title('dilated gradient mask');

```

A.3 SCRIPT FOR VELOCITY CALCULATION

```
close all, clear
```

```
%Load and display original images
```

```
I01 = imread('AAA_0001.BMP');
```

```
I02 = imread('AAA_0002.BMP');
```

```
I03 = imread('AAA_0003.BMP');
```

```
I04 = imread('AAA_0004.BMP');
```

```
I05 = imread('AAA_0005.BMP');
```

```
I06 = imread('AAA_0006.BMP');
```

```
I07 = imread('AAA_0007.BMP');
```

```
I08 = imread('AAA_0008.BMP');
```

```
I09 = imread('AAA_0009.BMP');
```

```
I10 = imread('AAA_0010.BMP');
```

```
%Set Minimum x, y, height and width
```

```
R = [0 400 1280 125]
```

```
%crop all images
```

```
C01 = imcrop(I01, R);
```

```
C02 = imcrop(I02, R);
```

```
C03 = imcrop(I03, R);
```



```
C04 = imcrop(I04, R);
```

```
C05 = imcrop(I05, R);
```

```
C06 = imcrop(I06, R);
```

```
C07 = imcrop(I07, R);
```

```
C08 = imcrop(I08, R);
```

```
C09 = imcrop(I09, R);
```

```
C10 = imcrop(I10, R);
```

```
%Define Big Matrix
```

```
l=1;
```

```
VEL(l:l+125,1:1280)=C01;
```

```
l = l+126;
```

```
VEL(l:l+125,1:1280)=C02;
```

```
l = l+126;
```

```
VEL(l:l+125,1:1280)=C03;
```

```
l = l+126;
```

```
VEL(l:l+125,1:1280)=C04;
```

```
l = l+126;
```

```
VEL(l:l+125,1:1280)=C05;
```

```
l = l+126;
```

```
VEL(l:l+125,1:1280)=C06;
```

```
l = l+126;
```

```
VEL(l:l+125,1:1280)=C07;
```

```
l = l+126;
```

```

VEL(1:1+125,1:1280)=C08;

l = l+126;

VEL(1:1+125,1:1280)=C09;

l = l+126;

VEL(1:1+125,1:1280)=C10;

l = l+126;

VEL(1:1+125,1:1280)=255;

l = l+126;

VEL(1:1+125,1:1280)=255;


figure(1), imshow(VEL)


%Perform Histogram Equalization

VELEQ = histeq(VEL);


%adjust contrast

VELCON = imadjust(VELEQ, stretchlim(VELEQ), [0 1]);

%figure(4), imshow(I4), title('contrast adjusted')


%Perform Edge Detection

%A=.17; %threshold multiplier

%BW = edge(VELCON, 'sobel',graythresh(VELCON)*A);

%figure(5)

%imshow(BW)

```

```
%title('Detected Edges')

%using strel and imdilate to dilate the image

%se90 = strel('line', 3, 90);

%se0 = strel('line', 3, 0);

%BWsdil = imdilate(BW, [se90 se0]);

%figure(6), imshow(BWsdil), title('dilated gradient mask');

figure(2), imshow(VELCON)
```

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